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Feasibility of Red Tide Detection Around Korean Waters Using Satellite Remote Sensing

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The monitoring activities at the National Fisheries Research and Development Institute (NFRDI) in Korea have been extended to include all the coastal waters of Korea after the outbreak of *Cochlodinium polykrikoides* blooms in 1995. We used several alternative methods including climatological analysis, spectral and optical methods which may offer potential detection of the major species of red tide in Korean waters. In the climatological analysis, NOAA, SeaWiFS, OCM satellite data was chosen using the known *C. polykrikoides* red tide bloom data and the area was mapped by helicopter reconnaissance and ground observation. The relationship between the distribution of sea surface temperature to *C. polykrikoides* bloom areas was studied. The anomalies of SeaWiFS chlorophyll *a* imageries against the imageries of non-occurring red tide for August, 2001 showed where the *C. polykrikoides* occurred. The anomalies of chlorophyll *a* concentrations from the satellite data during red tide outbreaks showed a similar distribution of *C. polykrikoides* in the red tide in August, 2001. The distribution between differences in sea surface temperatures during the day and at night also showed a possibility for red tide detection. We used a corrected vegetation index (CVI) to detect floating vegetation and submerged vegetation containing algal blooms. The results of from the optical absorption of *C. polykrikoides* in the ultraviolet band (340 nm) showed that if we use the optical characteristics from each red tide, we will be able to establish the feasibility of red tide detection.

Key words: *Cochlodinium polykrikoides*, Red tide, Satellite remote sensing

Introduction

Korea has experienced 11 occurrences of red tide (*Cochlodinium polykrikoides*) within an 11 year perid (1993-2003). This species has presented itself frequently in all of the southern coastal areas of the Korean peninsula and has been moving up the southeastern coasts and into the northeastern coasts since 1995 (Fig. 1 and Table 1). This phenomena shows that red tide is spreading and becoming more common, not only in the nearby coastal waters, but also in offshore areas, as well.

The monitoring activities of the National Fisheries Research and Development Institute (NFRDI) in Korea have been extended to include all coastal waters off Korean after the worst outbreaks of fish fatalities caused by the *C. polykrikoides* blooms in 1995. In order to mitigate red tide impacts, the ability to monitor algal blooms and to forecast the occurrences and the spread of red tides is required. Recently, the NFRDI is looking forward to establishing the feasibility of red tide detection within Korean waters using satellite remote sensing with NOAA/AVHRR (Advanced Very High Resolution Radiometer), Orbview-2/SeaWiFS (Sea Viewing Wide Field-of-View Sensor), IRS-P4/OCM (Ocean Colour Monitor) and Terra/MODIS (Moderate Resolution Imaging Spectroradiometer) on a real time basis (Fig. 2).

For remote sensing to be effective, red tides must be detectable, either directly through their effects on the water's color, or indirectly by correlation with algal blooms or association with a water mass that can be monitored by other remotely sensed characteristic such as sea surface temperature (Tester et al., 1991; Keafer and Anderson 1993; Suh et al., 2003).

In this study, several alternative methods were used

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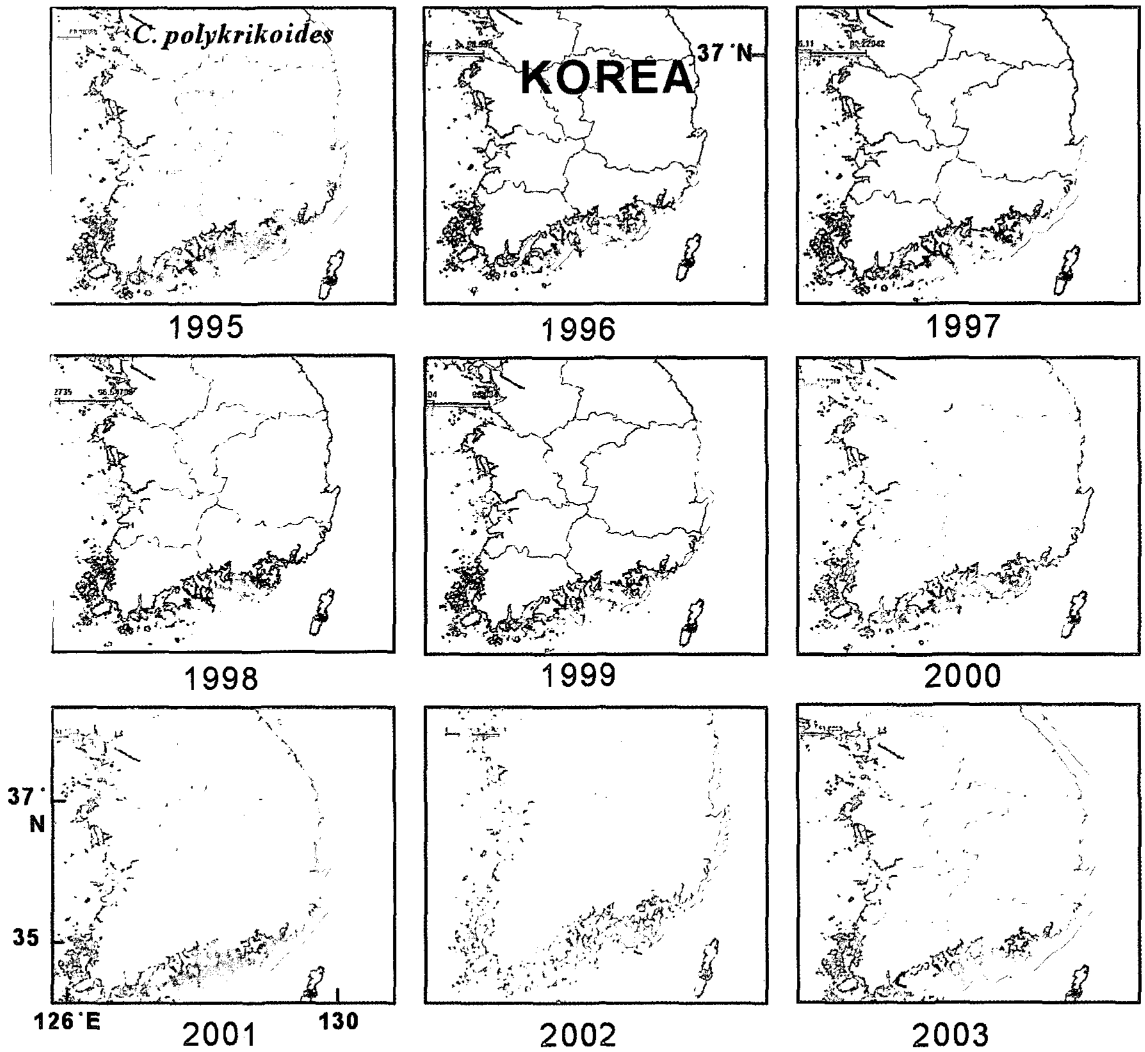


Fig. 1. Spatial distributions of the red tide (*C. polykrikoides*) occurrence around the Korean coastal waters in summer during 1995-2003. Red color appears the areas of red tide occurrence.

including a climatological analysis, spectral and optical methods which may offer potential detection of the major species of red tide in Korean coastal waters.

Materials and Methods

The NFRDI has been operating five different earth observing satellite receiving stations. The NFRDI can access sea surface temperature (SST) information derived from NOAA and GMS-5 satellites, and receive ocean color information from Korean waters derived from SeaWiFS, MODIS and Indian OCM satellites on a real time basis respectively.

SST data was derived from the infrared channels of an AVHRR sensor on NOAA satellites from 1995 to 2002 (Suh et al., 2000; McClain et al., 1985). There were two channels (channel 1 (ch1): 571-686 nm, and channel 2 (ch 2): 713-989 nm) on the AVHRR which were applied to ocean color remote sensing in 1995. In this case, we used the band ratio (ch1/ch2) to detect the major species of algal bloom, *C. polykrikoides*, *Ceratium furca* and *Notiluca* in 1995 based on Gallegos' thesis (1990).

To estimate chlorophyll *a* derived from SeaWiFS and OCM data was analyzed using the ocean color chlorophyll 2 algorithm, OC2 (O'Reilly et al., 1998). In the climatological analysis, the estimated chlorophyll *a* concentration derived from the ocean color satellites for red tide occurring during the day was compared to that of the preceding day's data. The

Table 1. The first day when red tide occurred at each station in the southern coast and in the eastern coast of the Korean peninsula

	← The southern coast							→		← The eastern coast							→	
Coast / Year *	Wan-do		Narodo		Nam-hae		Geje-do		Busan		Kung-ju		Yong-duk		Juk-byun		Dong-hae	**
1995	21st	7th	← 1st → (29, Aug.)	→	6th	→	12th	→	18th	→	24th	→	28th	→	29th	→	41st	55
1996	14th	12th	← 1st → (4, Sep.)	3rd	4th	→	10th	→	11th	15th	21st							28
1997	11th	←	5th	1st (24, Aug.)	→	→	2nd	→	6th	11th	17th	19th						27
1998	4th	2nd	← 1st → (30, Aug.)	9th	18th	20th	28th											34
1999	17th	15th	1st (10, Aug.)	→	→	5th	11th	→	18th	→	19th	→	→	→	23rd			54
2000			2nd	1st (22, Aug.)	3rd	12th	→	17th	→	18th								29
2001			1st (14, Aug.)	→	2nd	→	8th	→	10th	→	11th	→	13rd	→	15th	→	21st	42
2002	18th	←	1st (2, Aug.)	→	2nd	8th	11th	→	14th	→	19th	21st	26th					57
2003	3rd	←	←	1st (13, Aug.)	2nd	→	8th	→	14th	→	15th	→	17th	→	20th	→	22nd	62

*The day which red tide appeared at each station after the first day red tide occurred at the Narodo Island in summer season.

**Persistence of the red tide (days).

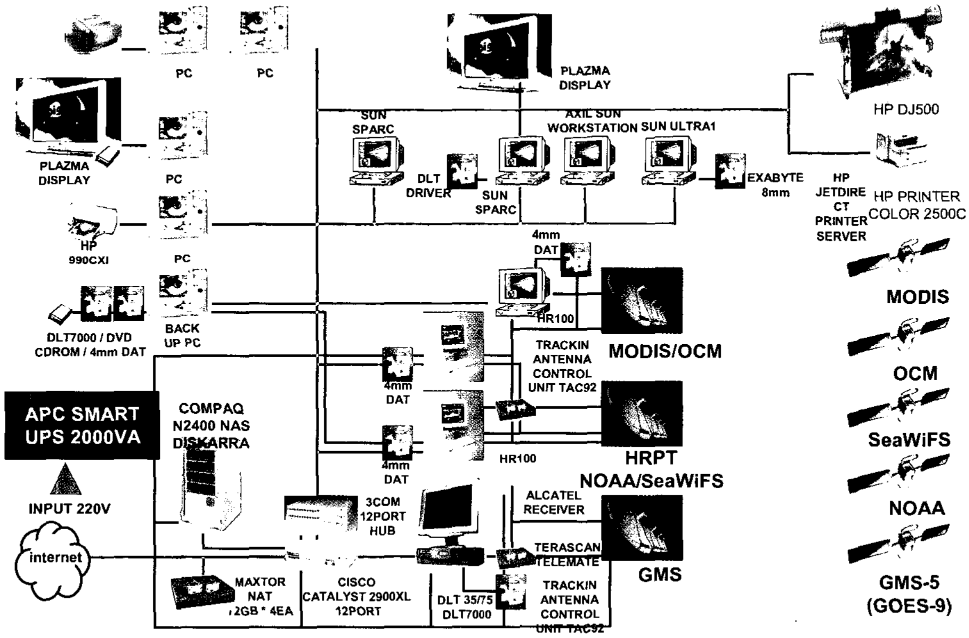


Fig. 2. Marine remote sensing system in National Fisheries Research & Development Institute, Korea.

distribution of the SST vaiations derived from the NOAA infrared data between daytime and nighttime red tides occurring in coastal waters was made to indirectly detect the distribution of algal bloom using the biological characteristics of the daily vertical migration of phytoplankton.

The absorption spectra (between 250 nm and 800 nm) of the *C. polykrikoides*, *H. akashiwo* and *P. minimum* was measured using a spectrophotometer (Varian Carry 100).

Results and Discussion

Current speed and direction, coastal upwelling of cold water

On occasion, we deployed an Argos satellite tracking buoy to measure sea surface current. It took almost 15 days to travel from the southern part to the northern part of the Korean waters (Fig. 3). Actually, cold water upwelling occurred in the south-eastern part of Korean waters while red tide was extending from the southern part to the northern part in the summer season of, 1995 and 1999. However, in the case of the 2001 survey, there was no upwelling of cold water when the red tide occurred in the summer season (Fig. 4). We can assume, no upwelling of cold water means the red tide was spread by warm currents without any prevention such as that of Ekman transport or the minimum water temperature related to the coastal upwelling of cold water in 2001.

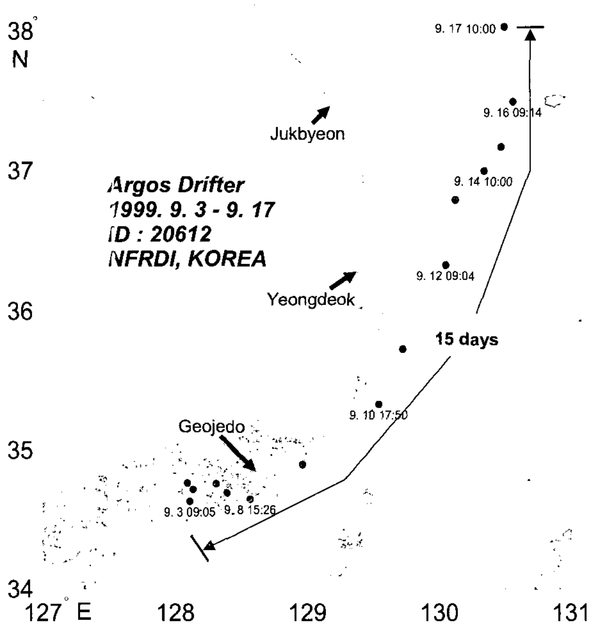


Fig. 3. Trajectory of the Argos-tracked drift buoy is shown during September 3-17, 1999. It took around 15 days from the first point to the last point by the drifting on the current. This speed of drifting is very similar to the spread speed of red tide from the south eastern coast to the north eastern coast of Korean waters in August, 2001 (Suh et al., 2003).

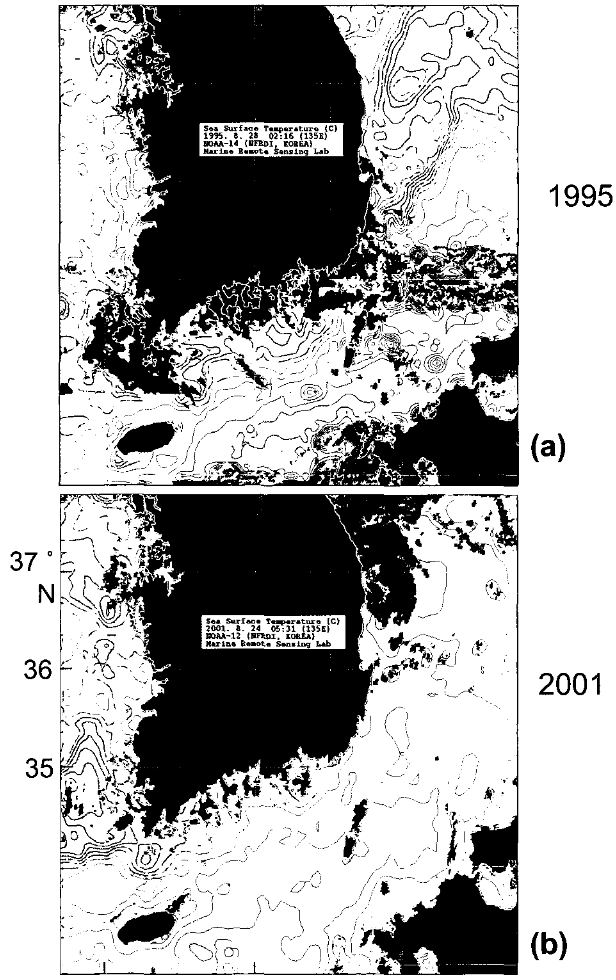


Fig. 4. SST imageries derived from NOAA satellite when huge red tide occurred in August, 1995 and 2001. These SST charts show the variations of upwelling cold water related to the distribution of red tide in the eastern coastal areas of the Korean peninsula; (a) The upwelling cold water occurred in August, 1995; (b) However, the cold water did not occur August, 2001. We can assume that the red tide was easily spread by warm current without any preventing of the coastal upwelling cold water in the south-eastern coast of the Korean peninsula in 2001 (Suh et al., 2003).

In 1997, the red tide which occurred in the southern coastal area had to remain in front of the coastal upwelling of cold water or move offshore. The red tide suddenly arrived within the northeastern coastal region of the Korean waters as soon as the upwelling

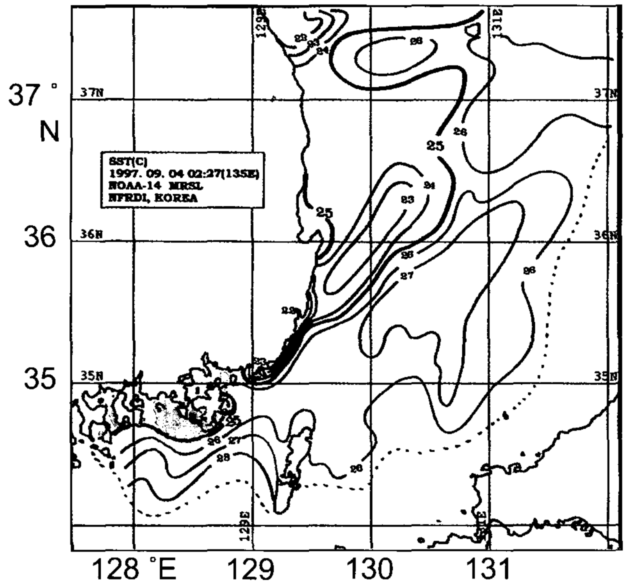


Fig. 5. *Cochlodinium polykrikoides* bloom (red areas) and NOAA SST (blooming area: Namhaedo 120-1,500 cells/mL, Saryangdo 2,000-10,500 cells/mL, Kojedo 500-5,000 cells/mL, Sept. 4th, 1997).

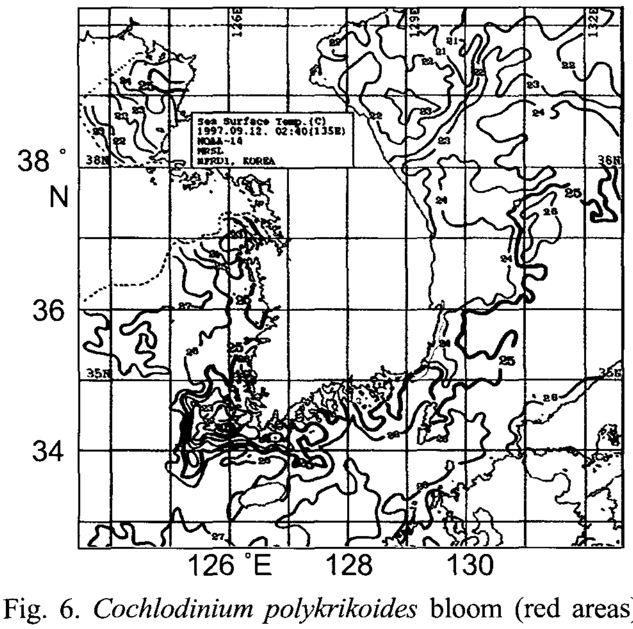


Fig. 6. *Cochlodinium polykrikoides* bloom (red areas) and NOAA SST (blooming area: Narodo 300-2,200 cells/mL, Kadokdo-Pohang 5,100-21,900 cells/mL, Sept. 12th, 1997) .

coastal cold water disappeared (Fig. 5 and 6).

Again, in 1995, after the upwelling cold water disappeared, the red tide also occurred in the south-eastern part of the Korean waters on September 21st and then, the red tide suddenly appeared in the northeastern coast after 5 days, on September 26th. The appearance of red tides in these areas, between the southern and northern coastal waters of Korea, was due to the East Korean Warm Current, which was moving offshore from the southern area and approached the northern region (Fig. 7).

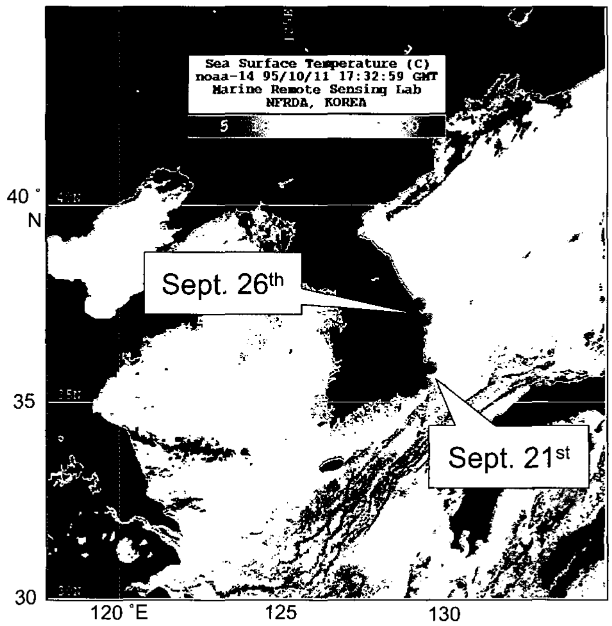


Fig. 7. Sea surface temperature derived from NOAA satellite (Oct. 11th, 1995). *Cochlodinium polykrikoides* bloom (red cycles). Blooming area: Yangnam at Kyongju-Sukbyoeng at Pohang, 630-2,200 cells/mL, Sept. 21st, Kunduck at Samchuk-Chunkog at Donghae, 300-1,300 cells/mL, Oct. 8th, 1995.

Harmful algal bloom in Korean coastal waters in 2001

Cochlodinium polykrikoides bloom was observed by aircraft and vessels cruising in Korean coastal waters in 2001. The blooms occurred in several coastal areas in the southern part of Korean waters on August 20th, 2001. After just 6 days, on August 26th, the blooms extended from southern to southeastern regions (Fig. 8). The dark red mark represents a density of *Cochlodinium polykrikoides* of more than 3,000 cell/mL and the other mark represents lower densities.

Fig. 9 is the estimated chlorophyll *a* derived from the Indian Ocean Color Monitor (OCM) using the

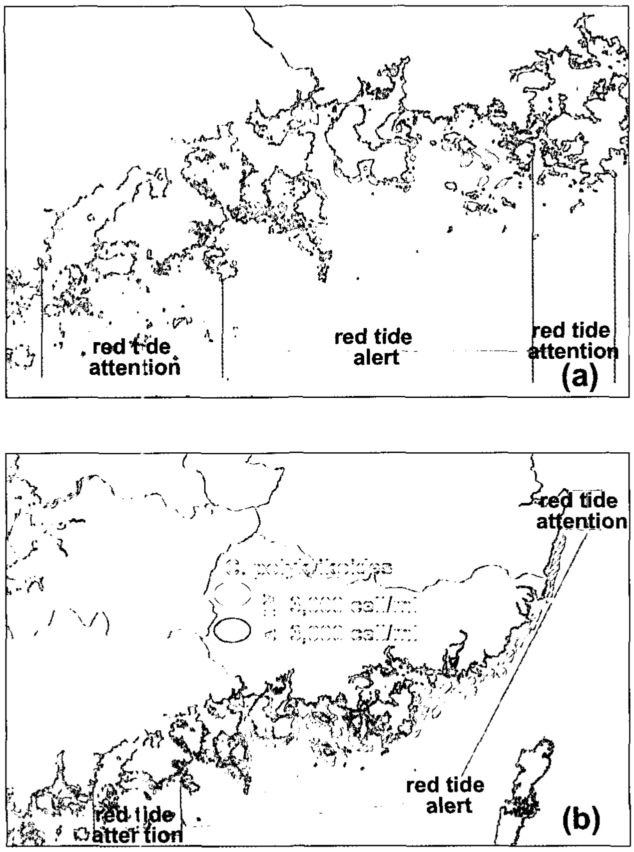


Fig. 8. Distributions of harmful algal bloom in Korean coastal waters (a) August, 20th and (b) August 21st, 2001. *C. polykrikoides* red tide bloom area mapped by helicopter reconnaissance and ground observation.

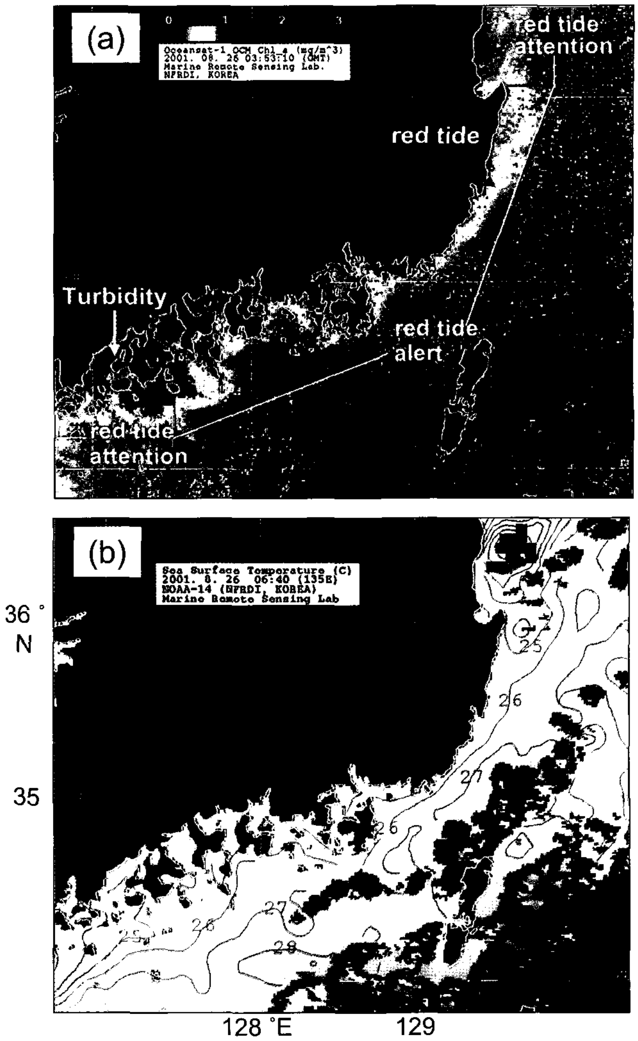


Fig. 9. (a) Distributions of chlorophyll *a* (mg/m^3) and (b) sea surface temperatures (℃) in the southern and southeastern parts of the Korean peninsula in August, 2001.
(a) The spatial distribution of in situ red tide was quite well matched up to the green color on the imagery and (b) the boundary between 25 and 26 isothermal line on the imagery.

OC 2 algorithm. The OCM sensor is similar to the SeaWiFS excluding the spatial resolution of the 360 meter and 2 days revisiting cycle. We can see very similar feature distributions with the red tide blooms in the isothermal lines between 25℃ and 26℃ as estimated by the NOAA satellite. However, the estimated chlorophyll *a* density was just less than 1 mg/m^3 in the red tide bloom areas based on this image. It would actually be of little use to monitor the *Cochlodinium polykrikoides* red tide if we want to detect red tide with information from the estimated chlorophyll *a* density derived from the IRS-P4/OCM satellite.

Time series of chlorophyll *a* variation

Fig. 10 is a calendar of the chlorophyll *a* from early in January to the last ten days in December, 2000 (Fig. 10a and 10b) and 2001 (Fig. 10c and 10d) using SeaWiFS data. We can detect the spring bloom of phytoplankton in April and May. However, we can not notice any special activities from August to September while the *Cochlodinium polykrikoides* red tide blooms occurred frequently. Stations were established to extract the time series data from the SeaWiFS chlorophyll *a* images from 2000 to 2001 (Fig. 10e). We averaged chlorophyll *a* values in an 18×18 km area to avoid some noise on the images. We also quantified the seasonal variations of SeaWiFS chlorophyll *a*. We were able to detect the spring bloom in March, May and the late fall bloom in

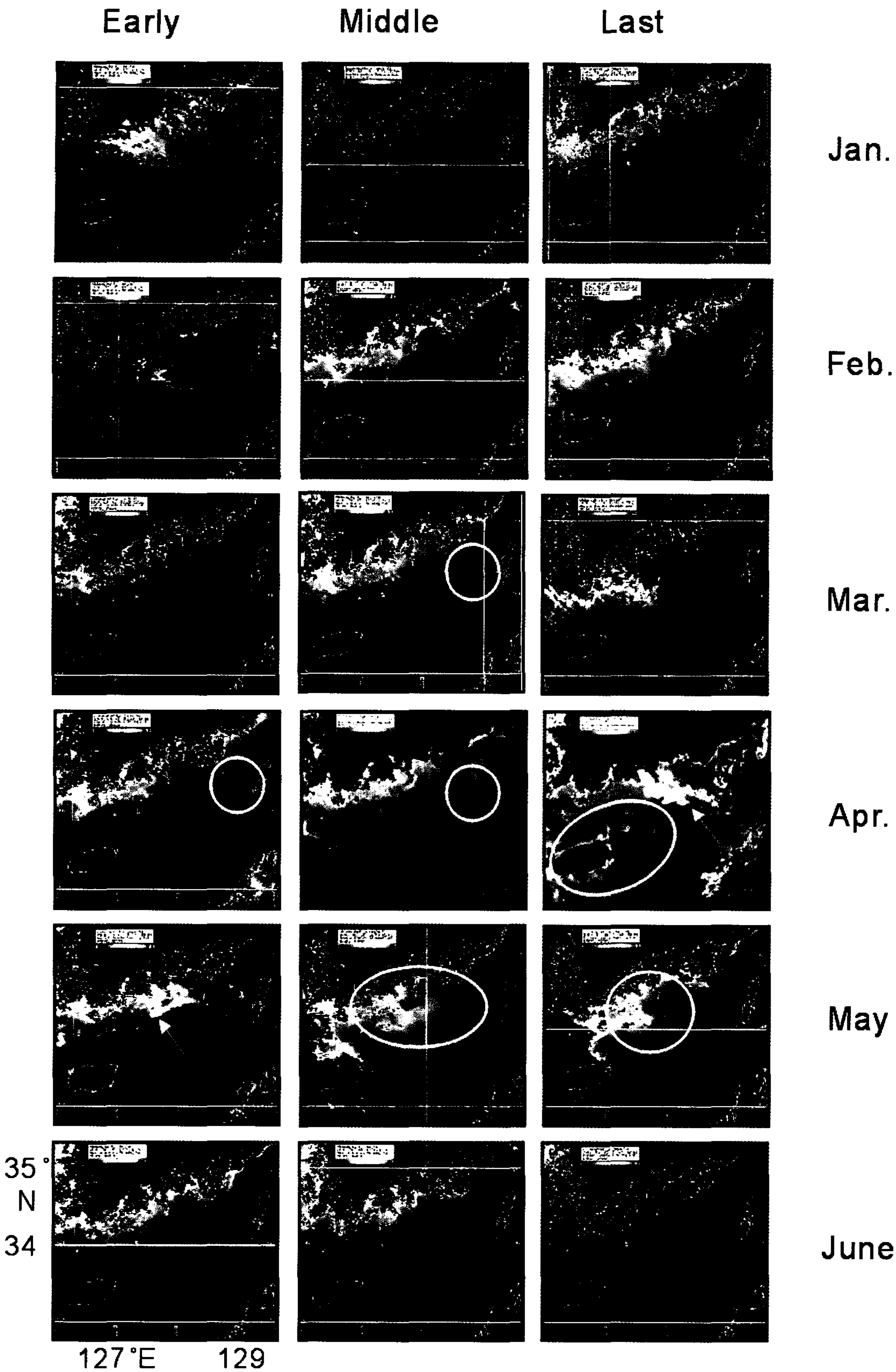


Fig. 10a. Ten days imageries of the estimated chlorophyll *a* derived from SeaWiFS in Jan.-Jun., 2000.

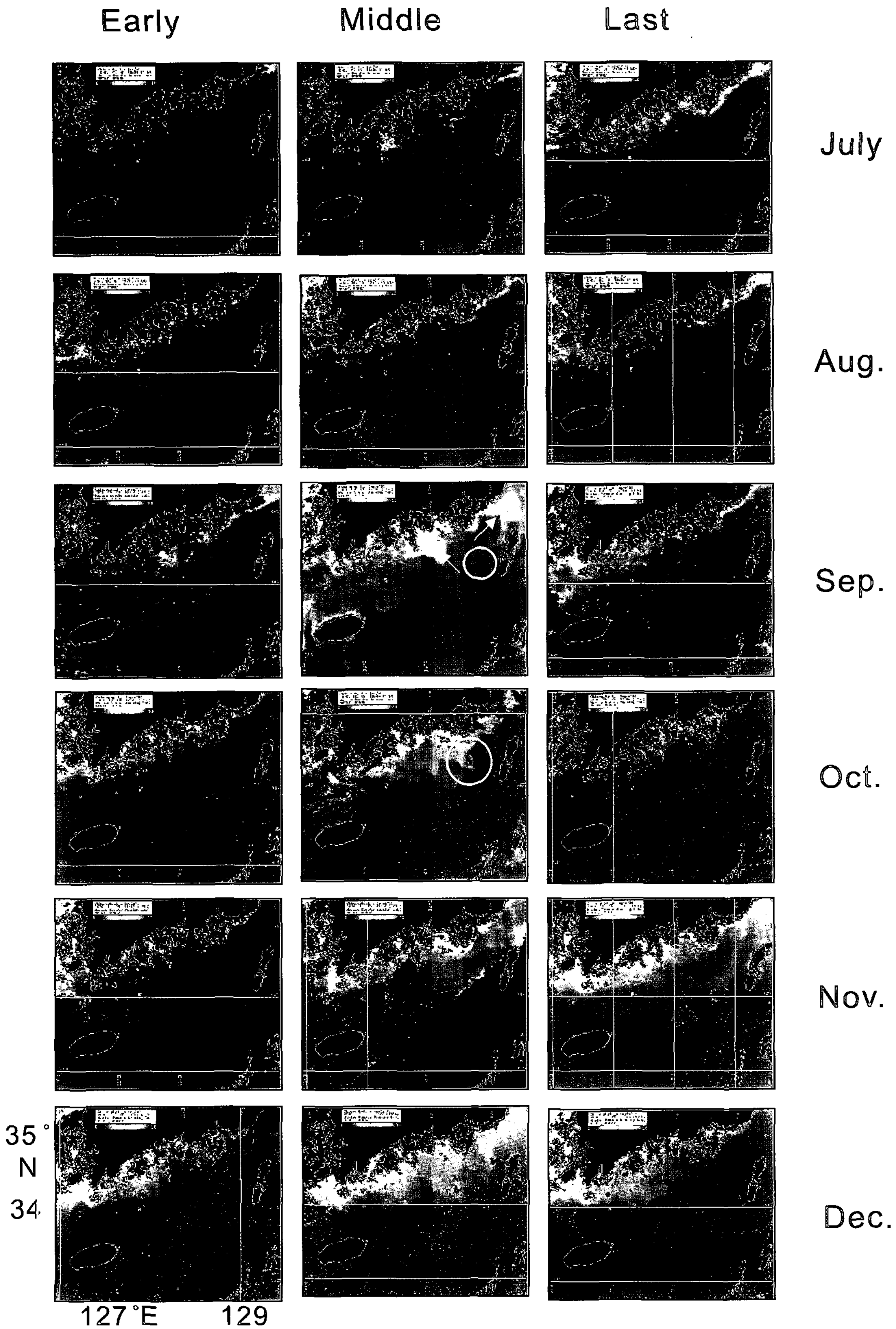


Fig. 10b. The same as Fig. 10a, except for Jul.-Dec., 2000.

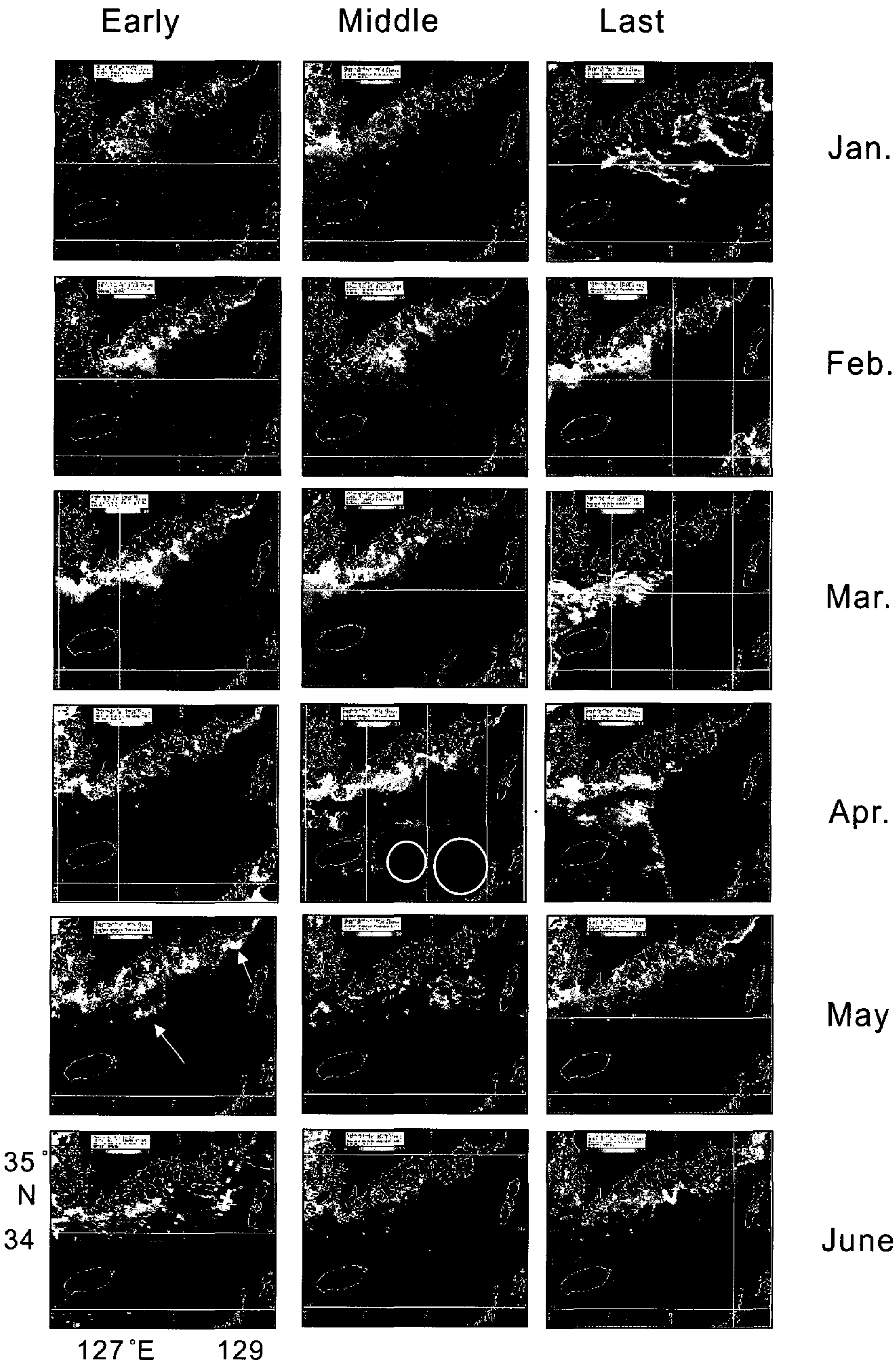


Fig. 10c. The same as Fig. 10a, except for 2001

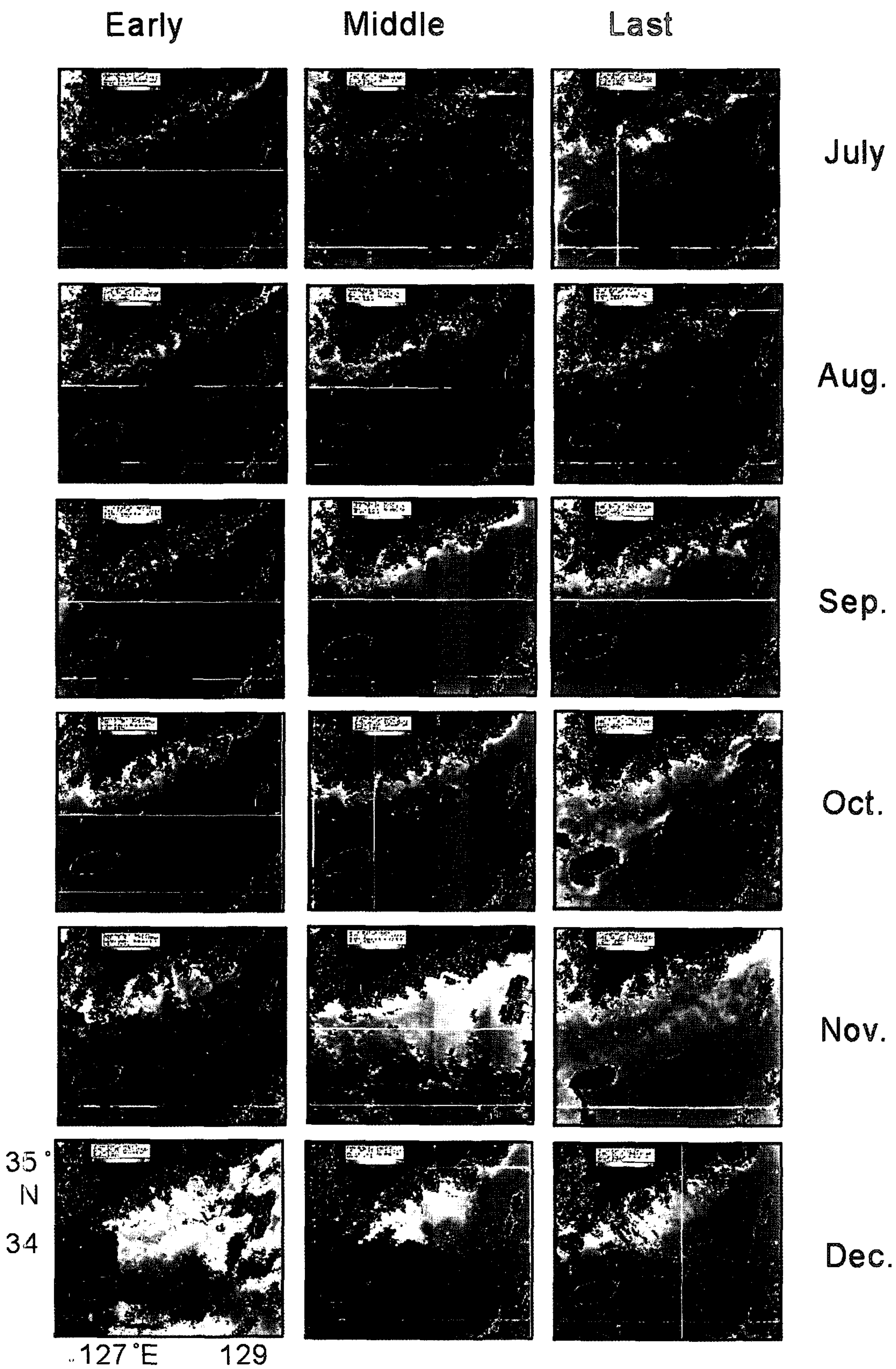


Fig. 10d. The same as Fig. 10b, except for 2001.

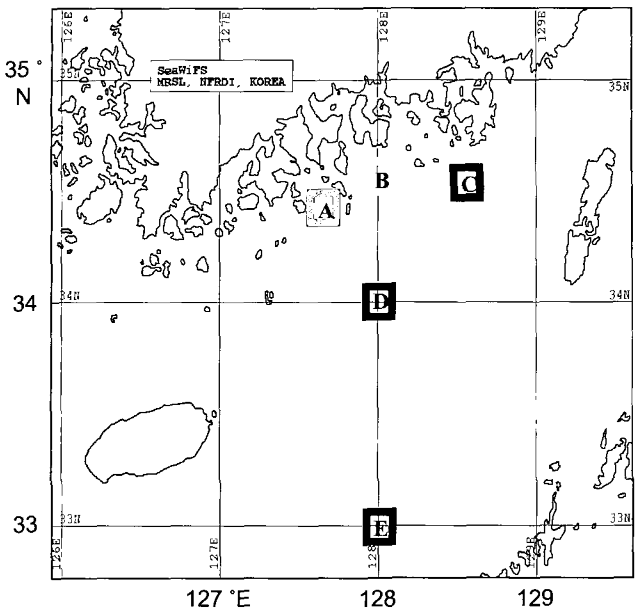


Fig. 10e. Study map in the southern part of the Korean waters. Each sample station, A, B, C, D and E has 18 km in area of the estimated chlorophyll *a* from the SeaWiFS images.

December, 2000-2001. However, we were not able to establish the high chlorophyll *a* density during the summer even though huge red tides occurred in 2000 and 2001 (Fig. 11).

Delta chlorophyll *a* distribution on the date of red tide occurrences

Fig. 12 shows the different levels of chlorophyll *a* based on readings taken before the *Cochlodinium polykrikoides* red tide occurred on August 20th, and after the red tide occurred on August 26th, 2001. We were able to see that the differences in the distributions were about 60% similar to the observed red tide distributions made in the field on August 26th, 2001. Specifically, the differences in the distributions from 2 to 6 mg/m^3 were similar to the distributions of the red tide data recorded in the field.

Local heating caused by red tides

We would like to talk about our theory of the local heating effect caused by red tides. Sometimes local heating occurs at the sea surface layer in shallow coastal water which is shallower than 20 m at daytime during the summer season, like those shown in Fig. 13a. However, there was local heating at levels deeper than 20 m. Phytoplankton, red tide has a vertical migration, in general. Even though red tides are at deeper layers at night, they return to the surface layer

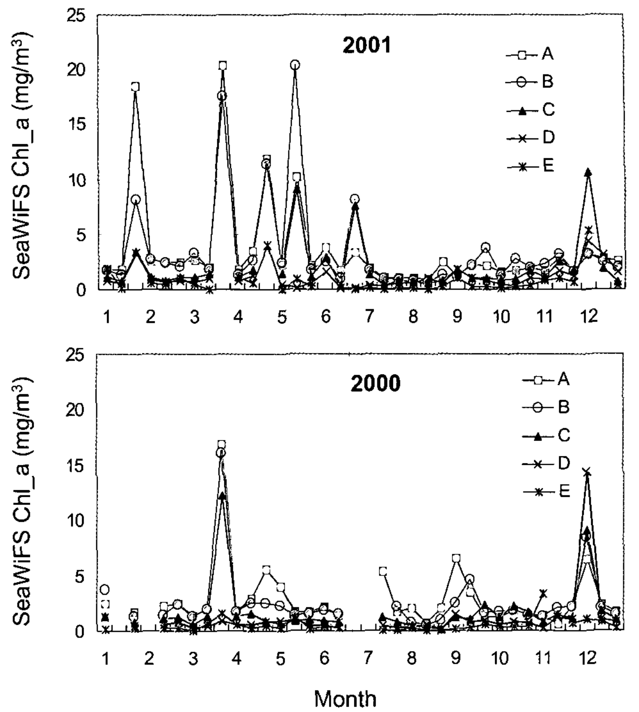


Fig. 11. Ten days variations of the estimated chlorophyll *a* derived from SeaWiFS in 2000 and 2001.

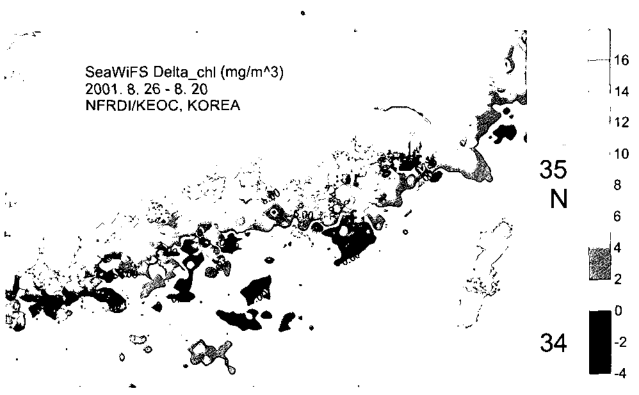


Fig. 12. Distribution of difference in chlorophyll *a* between before *Cochlodinium polykrikoides* red tide occurring, in August 20th and after the red tide occurring in August 26th, 2001.

(between 0 and 5 m) during the day to perform photosynthesis. Therefore, we think sea surface local heating can occur due to the role red tides play on sea bottoms shallower than 5 m during the day and during the summer season (Fig. 13b).

Fig. 14 shows the differences of sea surface temperatures between daytime and nighttime in August 26, 2001, and the distribution of the iso-depth line.

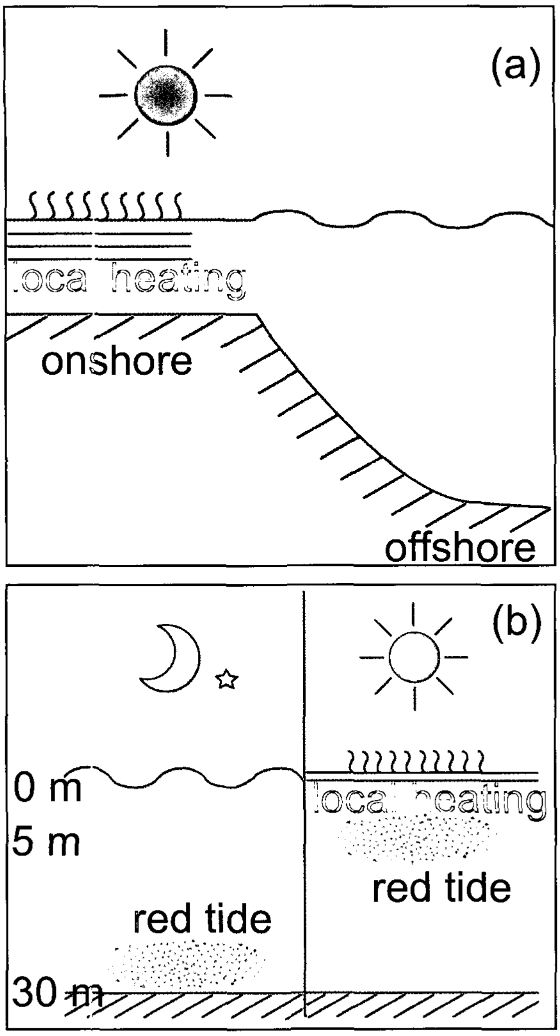


Fig. 13. (a) Local heating caused by shallow water at daytime. (b) Local heating caused by red tide at daytime.

Local sea surface heating occurs in water shallower than 20 m due to shallow bottoms in the coastal areas. However, if local heating occurs deeper than 20-30 m, we can assume that the local heating is being caused by red tides.

Suspended solids caused by red tides as organic materials

We would likes to talk about the feasibility of red tide detection using estimated suspend solids (SS) in the southern part of Korean waters. We developed the empirical formula from the relationship between the in situ SS and SeaWiFS band ratio (nLw490/ nLw555) as in Fig. 15. We were able to regenerate the suspended solid distributions in the southern part

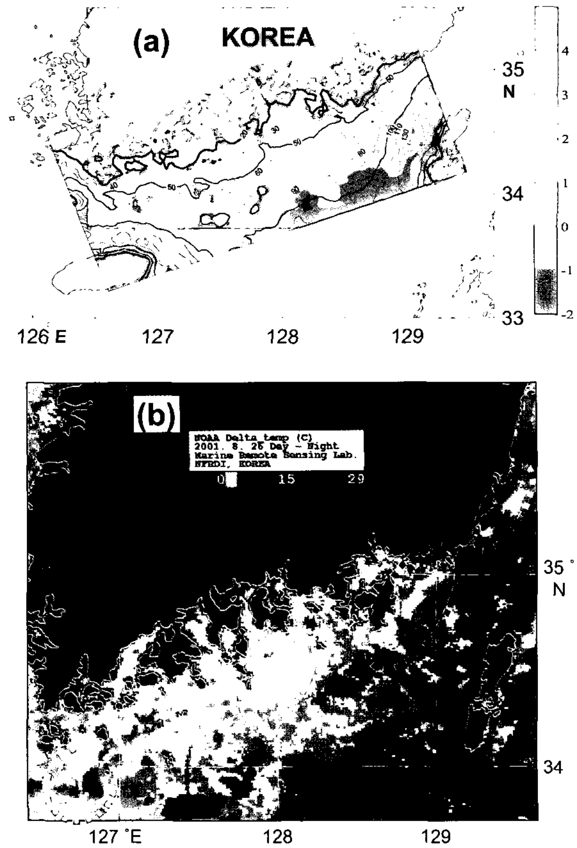


Fig. 14. (a) Bottom topography and delta temperature (Day-Night) in Aug. 26th, 2001. (b) Estimated area of red tide occurrence (◌) on the imagery of delta temp (℃) in Aug. 26th, 2001

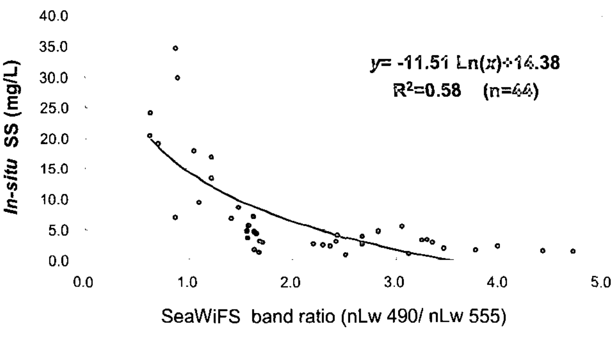


Fig. 15. Empirical relationship between in situ suspended solid in the southern part of the Korean waters and band ratio of SeaWiFS satellite from October 1999 to June 2002.

of Korean waters using the empirical formula [Estimated SS=-11.51 Ln(x)+14.38, R^2=0.58, here x is the SeaWiFS band ratio (normalized water leaving radiance 490 nm/555 nm)]. We were able to see the feature of yellow color on the image in August 26th, 2001. It seems that the distribution of yellow color is quite similar to red tide distribution, excluding some parts of the southwestern sea of the Korean waters. We were able to compare this satellite image with red tide distributions. The yellow colored areas are *Cochlodinium polykrikoides* red tide distributions (Fig. 16).

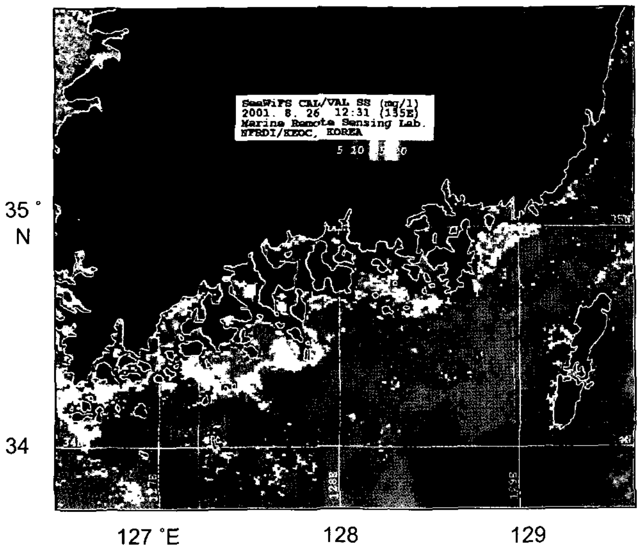


Fig. 16. Estimated suspended solid (SS) and red tide distribution in August 26th, 2001. Distributions of yellow color parts more than SS concentration with 17 mg/L are estimated to red tide distribution.

Spectral analysis to directly detect red tides in Korean waters

A spectral analysis to directly detect red tides in Korean waters was studied. We did a feasibility study using a simple spectral band ratio of NOAA channel 1 and 2.

Huge *Cochlodinium polykrikoides* blooms occurred during the summer of 1995. On the other hand, Noctiluca scintillans blooms also occurred around the coastal waters in Busan, Korea. The density of the Noctiluca scintillans bloom was around 400 cell/mL. Very red colored water was observed, not unlike the color of tomato juice, while the Noctiluca bloom occurred. We were able to achieve fairly good results using a simple band ratio of the NOAA red 1.6 times the normal value represented the distribution of the Noctiluca bloom in 1995 (Fig. 17).

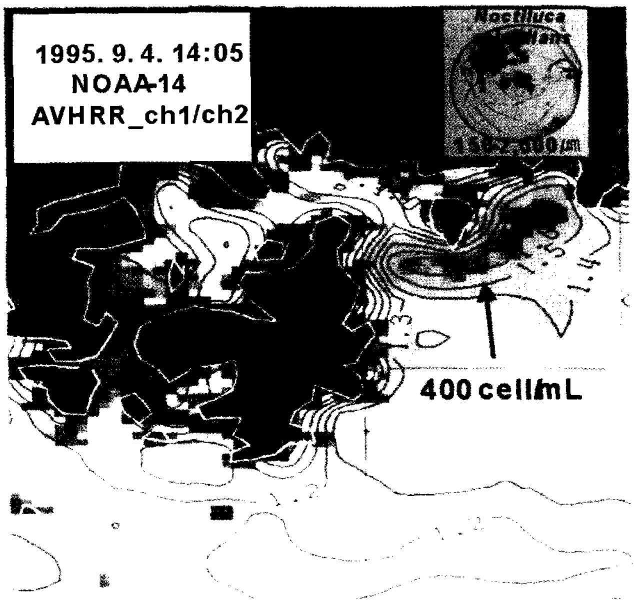


Fig. 17. Geographical distribution of AVHRR ch1/ch2 ratio to detect red tide, Noctiluca scintillans.

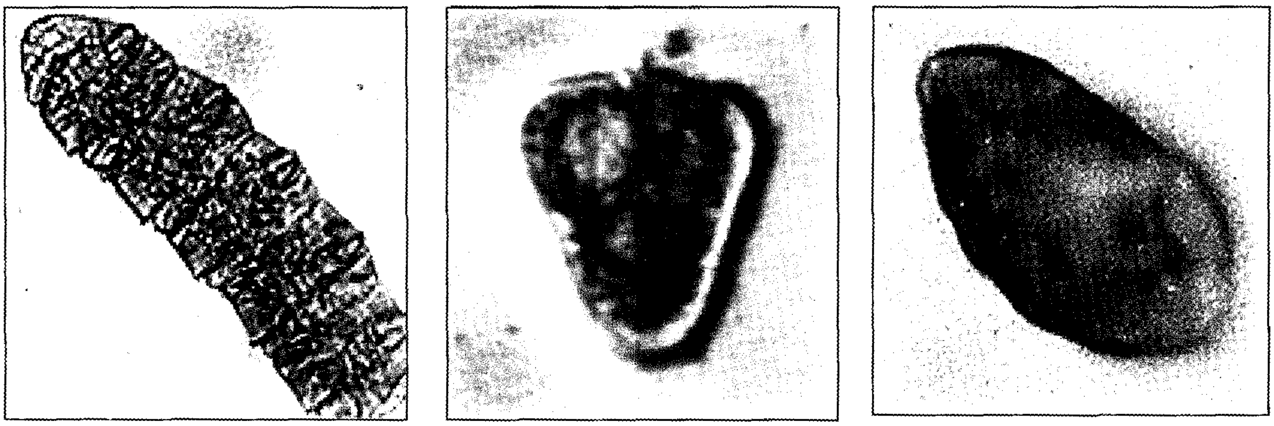
Optical analysis to directly detect red tides in Korean waters

An optical analysis to directly detect red tides in Korean waters was studied. We attempted to establish the optical characteristic of different red tide species using optical absorption and marker pigments.

There are several major species of red tides in Korean waters. Among them, *C. polykrikoides* is the band and near the IR band. A range of more than major species while others such as *Prorocentrum minimum* and *Heterosigma akashiwo*, also exist (Fig. 18). We measured optical absorption and pigment using an UV (UltraViolet) spectral photometer and a HPLC (High Performance Liquid Chromatograph System) at our laboratory. We were unable to establish the significant bands from 250 nm to 800 nm for the absorption spectra of *P. minimum* (Fig. 19a) and the *H. akashiwo* species excluding general absorption in 680 nm (Fig. 19b).

However, in the case of the *C. polykrikoides*, there was a significant absorption spectra around 350 nm in each density of 1,000, 3,000, and 6,000 cells/mL (Fig. 19c). If we focus on this UV band, it may be feasibility to detect the major species of red tides in Korean waters.

Fig. 20 shows that the dinoflagellate class including *C. polykrikoides* is classified by a peridinimum pigment among the 3 species. However, we could not



Cochlodinium polykrikoides
Size: 30-40 μm
Season: summer
Class: Dinoflagellates

Prorocentrum minimum
Size: 15-23 μm
Season: summer
Class: Dinoflagellates

Heterosigma akashiwo
Size: 8-25 μm
Season: spring-fall
Class: Chrysophytes

Fig. 18. Major species of red tide in Korean waters.

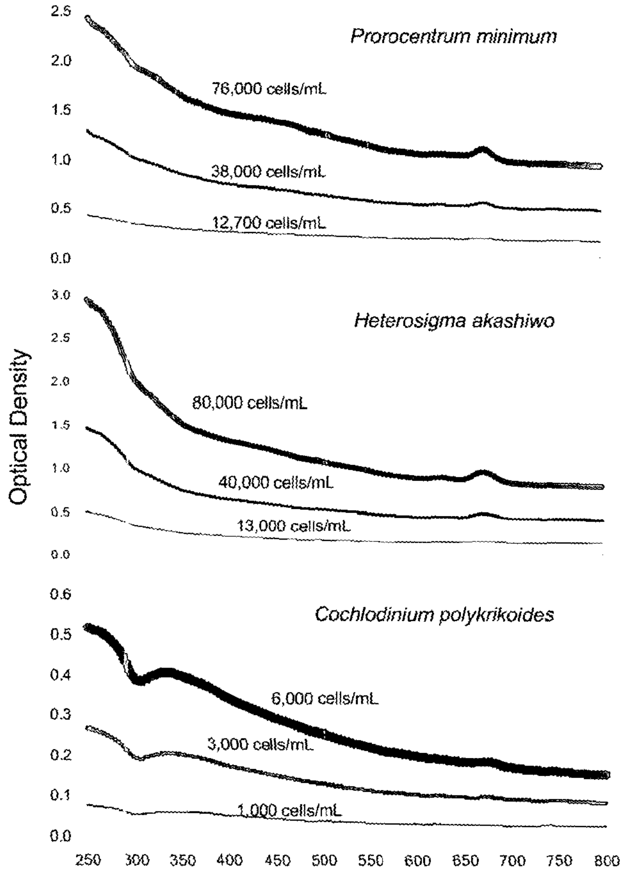


Fig. 19. Absorption spectra of *P. minimum*, *H. akashiwo* and *C. polykrikoides* between 250 nm and 800 nm.

classify the species between *P. minimum* and *C. polykrikoides* under same class of dinoflagellate using a HPLC method.

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References

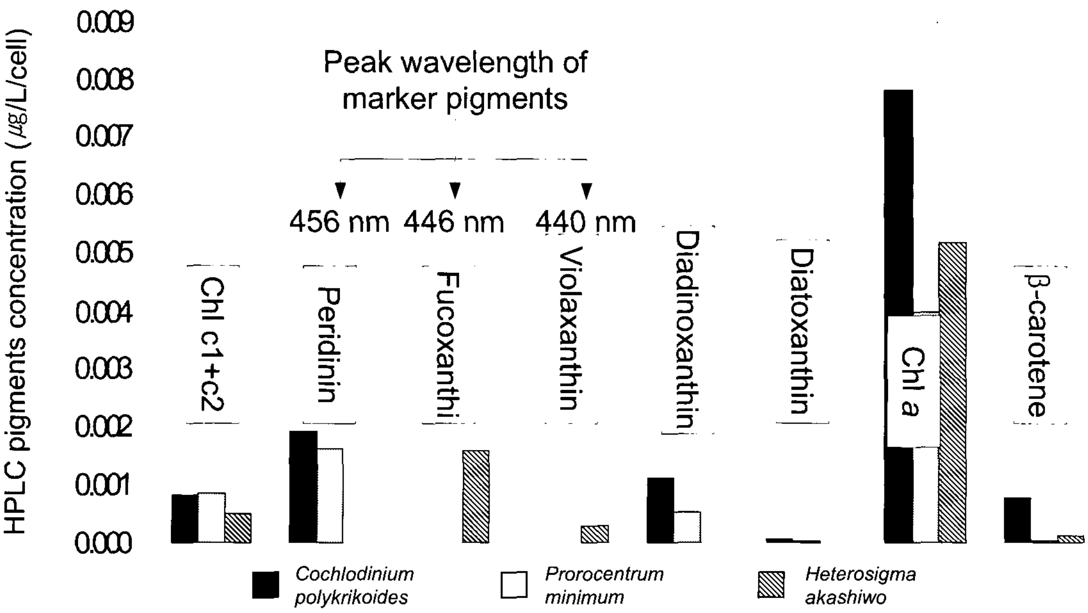
Gallegos, S.C., 1990. Evaluation of the potential of the NOAA-n AVHRR reflective data in oceanography. Ph.D. thesis, University Texas A. & M., pp. 88.

Keafer, B.A. and D.M. Anderson. 1993. The use of remotely-sensed sea surface temperatures for studies of *Alexandrium* bloom dynamics in the southwestern Gulf of Maine. In: Smayda T. and Y. Shimizu, eds. Toxic Phytoplankton Blooms in Sea, Elsevier, Amsterdam, The Netherlands, pp. 763-768.

McClain, E.P., W.G. Pichel and C.C. Walton. 1985. Comparative performance AVHRR based multi-channel sea surface temperatures, J. Geophys. Res., 90, 11,587-11,601.

O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru and C.R. McClain. 1998. Ocean color chlorophyll algorithms for SeaWiFS. J. Geophys. Res., 103, 24,937-24,953.

Suh, Y.S., J.H. Kim and H.G. Kim. 2000. Relationship between sea surface temperature derived from NOAA satellites and *Cochlodinium polykrikoides* red tide occurrence in Korean coastal waters. J. Kor. Environ. Sci. Soc., 9(3), 215-221.



Cochlodinium polykrikoides	0.0008	0.0019	None	None	0.0011	0.0001	0.0078	0.0008
Prorocentrum minimum	0.0009	0.0016	None	None	0.0005	0.00004	0.0040	0.00005
Heterosigma akashiwo	0.0005	None	0.0016	0.0003	None	None	0.0052	0.0001

Fig. 20. Classes of red tide organism were classified by pigments.

Suh, Y.S., L.H. Jang, N.K. Lee and B.K. Kim. 2002. Development of the regional algorithms to quantify chlorophyll *a* and suspended solid in the Korean waters using ocean color. J. Kor. Fish. Soc., 35(3), 207-215.

Suh, Y.S., L.H. Jang and H.G. Kim. 2003. Relationships between spatio-temporal distribution of *Cochlodinium polykrikoides* red tide and meso-scale variation of oceanographic environment around the Korean Waters. J. Kor. Associ. Geographic Information. Stud., 6(3), 139-150.

Tester, P.A., R.P. Stumpf and F.M. Vukovich et al. 1991. An expatriate red tide bloom: transport, distribution, and persistence. Limnol. Oceanogr., 36(5), 1,053-1,061.

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