In-situ and remote observation of *Cochlodinium.p* blooms and consequences of physical features off the Korean coast

Yu-Hwan Ahn, P. Shanmugam and Joo-Hyung Ryu
Satellite Ocean Research Laboratory
Korea Ocean Research and Development Institute, Seoul, 425-600, Korea
yhahn@kordi.re.kr

Abstract: Spatial and temporal aspects of toxic dinoflagellate *Cochlodinium.p* blooms and consequences of physical features in complex coastal ecosystems, off the southern Korean coast, have been investigated using data obtained from SeaWiFS and AVHRR as well as in-situ observations. Hydrographic parameters measured using CTD sensors were used to elucidate physical factors affecting the spatial distribution and abundance of *Cochlodinium.p* blooms. The results show spatial and temporal variations of chlorophyll-a (Chl-a) and sea surface temperature (SST) and reveal significant information about *Cochlodinium.p* blooms and process underlying their evolution. Satellite-derived Chl-a estimates appear to be potential in explicating the evolution, movement and distribution of *Cochlodinium.p* blooms in the enclosed bays of the South Sea. The existence of thromohaline waters offshore provide favorable conditions for the rapid growth and subsequent southward initiation of *Cochlodinium.p* blooms that are influenced to flow on the offshore branch (OB) during September. It was observed that there was a significant variation in the sun-induced chlorophyll-a fluorescence signal in the remote sensing fluorescence spectra and its high-intensity was recognized during the period of exponential growth and physical transport. Satellite-derived Chl-a concentration during September 1999 ranged between 3-60 mg/m^3 inside the Jin-hae and adjacent Bays and 1~6 mg/m^3 in offshore waters, with varying *Cochlodinium.p* abundances 1500 to 26000 cells ml^{-1}. The closely spaced CTD surveys and satellite-derived SST give a complete overview on the initiation of *Cochlodinium.p* blooms in hydrodynamically active regions of the offshore southern East Sea by the influence of Tsushima Warm Current (TWC).

Keywords: SeaWiFS, Cochlodinium.p blooms, warm current

1. Introduction

Phytoplankton blooms appear to be an increasingly common phenomena on a worldwide scale and are sometimes considered to be harmful either because of their potential threat to human health through the consumption of contaminated seafood, as in the case of many toxic phytoplankton blooms, or through the changes in species abundances and distributions (often including species of commercial value), as in the case of recent brown or red tide blooms (Buskey at al., 1996; Tester and Steidinger, 1997). The bloom formations occur, when the rate of phytoplankton growth exceeds the rate of cell dispersion, due to anthropogenic nitrification, as being one of the most pervasive changes altering coastal environments worldwide (Shumway, 1990; Burkholder, 1998), or steepening of nutricline by intervenes of physical phenomena (Falkowski et al., 1991; Seki et al., 2001; Olaizola et al. 1993). The semi-enclosed nature of the Korean Bays often reach extremity in eutrophic state by receiving terrestrial wastewater and pollutants, resulting in occurrence and outbreaks of harmful *Cochlodinium.p* blooms, which appear to have significantly increased in frequency, intensity and geographic distribution and caused massive mortalities of aquaculture fish off the southern and eastern coasts of Korea (Kim et al., 1999). Among several dinoflagellates species, *Cochlodinium.p* has been identified as the causative organism, of red tides, responsible for massive fish kills in warm temperate and tropical waters (Steidinger & Tangen 1996), and its monospecific nature with unique set of conditions results in the high rates of respiration that can cause dissolved oxygen concentrations to fall to a level low enough to endanger marine life (Buskey et al., 1996). Besides eutrophication, other changes in environmental conditions such as warming, resuspension of spores and advection are also principal factors for the increased occurrence of *Cochodinium.p* blooms in Korean coastal waters (Kim et al., 1990). Although there are historical records of red tides since the 6th century, the first scientific report on red tides was published (Park and Kim, 1967), and later, many red tide events have been documented along with an extensive red tide phytoplankton bloom in summer 1995, which caused heavy mortalities of aquaculture fish and amounted to a loss of ~US$ 95.5 million (Kim, 1997). Although *Cochlodinium.p* is known as the red tide species associated with extensive fish kills and great economic loss in Korean and Japanese coastal waters (Kim 1999; Yuki and Yoshimatsu 1989; Fukuyo et al. 1990), the actual toxin principles have yet to be elucidated (Taylor et al. 1995). However, numerous studies indicate that secretion of some ichthyologic substances by *Cochlodinium.p* species is believed to be a possible cause for fish kills (Onoue et al., 1985; Hallegraeff, 1992). Thus, mitigating the impacts of such harmful algal blooms is necessary and requires an ability to monitor blooms and to forecast their development and movement (Stumpf, 2001). In the present paper, we investigate spatial and temporal aspects of the potentially toxic *Cochlodinium.p* and other phytoplankton blooms of the South and East Seas and relate them to the physical processes using satellite and in-situ data.

2. Materials and Methods

The study area includes the southern coastal Bays of

Korea, which reveal high variability in physical, chemical and biological properties. Four cruises (R/V Olympic) coinciding with the blooms of *Cochlodinium.p* in August/September for the period 1998-2003 were conducted over the Jin-hae Bay and adjacent waters of the South Sea (Fig. 1). The ship surveys consisted of over 200 stations inside and outside the bloom. Seawater samples collected simultaneously with the radiometric measurements were analyzed for Chl-a concentrations using Perkin-Elmer Lambda 19 dual-beam spectrophotometer. The chlorophyll concentrations varied from 1 to 65 mg/m^3 around the Jinhae Bay, except for few locations close to the coast where it reached 207 mg/m^3 in August 1999 (Fig.2).

Several radiometric measurements, including water leaving radiance $L_w(\lambda)$, sky radiance $L_{sky}(\lambda)$ and downward spectral irradiance E_d (λ), were performed at various sample transects over these waters. The data L_{wT} (λ) recorded in units mW cm^{-2} μm^{-1} sr^{-1} were corrected for the sky light reflection and the air-sea interface effects, using the values of $L_{sky}(\lambda)$ obtained from the sky radiometer and assumed F_r value (0.025) (Austin (1974). The remote sensing reflectance was then obtained by normalizing the corrected water-leaving radiance ($L_w(\lambda)$ to downwelling irradiance (E_d) as follows $R_{rs}(0^+\lambda) = L_w(\lambda)/E_d(0^+\lambda)$. Example of remote sensing reflectance $R_{rs}(\lambda)$ spectra, measured in August 1999, corresponding to chlorophyll concentrations 0.8 ~28.3 mg/m^3, shows absorption maxima at 445nm and reflectance maxima at 567nm and sun-induced chlorophyll fluorescence peak maxima at 685nm (Fig. 3). Noteworthy, with the increase of Chl-a concentration the magnitude of the fluorescence peak also increases with a notable decrease towards the blue part of the spectrum, potential for developing algorithms using this signal.

In September 1999 when there was an occurrence of massive bloom of *Cochlodinium.p* in coastal waters of the South Sea and its offshore, CTD surveys were performed aboard the R/V EARDO to elucidate detailed hydrographic conditions during the bloom formations. Vertical sampling was made with CTD at most of the stations. Both the CTD- and the satellite-derived (AVHRR) sea surface temperature provided a complete overview of the prevailing hydrography and phytoplankton bloom dynamics off the southeastern coasts of Korea.

Level 1A SeaWiFS imageries were acquired from the KORDI satellite data receiving station for the periods 1998 to 2000. These data coincided with the rapid growth and outbreaks of *Cochlodinium.p* blooms of the Jin-hae Bay in August/September. The ocean color radiances were atmospherically corrected and processed to level 2 using NASA SeaDAS version 4.4. Surface Chl-a concentrations were then derived from the atmospherically corrected SeaWiFS data using NASA OC4v4 bio-optical algorithm (O'Reilly et al., 2000) within SeaDAS. Similarly, AVHRR infrared imageries collected simultaneously with the in-situ measurements were geo-referenced to a common grid and projection system at a spatial resolution of 1.1km and analyzed for SST using the split window MCSST dual channel algorithm (available with TerraScan software).

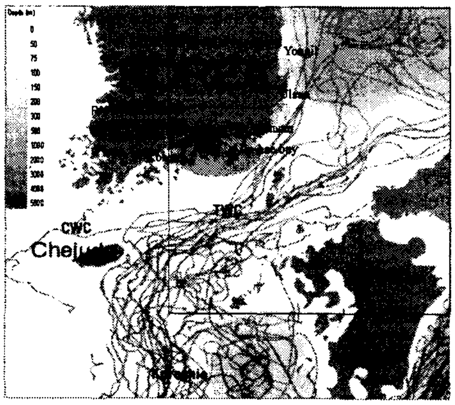


Fig.1. General patterns in sea surface current field observed from the satellite-tracked drifter trajectories in the East China and Yellow Seas during the period 1989 to 1996 (Lie et al. 2002). The shaded circles represent the areas of occurrence of red tides off the southeast and eastern coasts of Korea. In-situ measurements carried out in the Jin-hae Bay and surrounding waters during 1998-2003 are also indicated by an arrow mark.

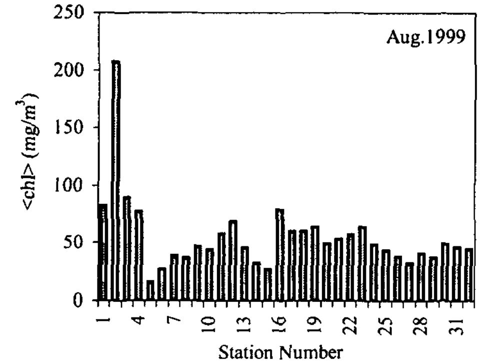


Fig.2 Spatial distribution of Chl-a concentration measured in red tide waters of the Jin-hae Bay during August 1999.

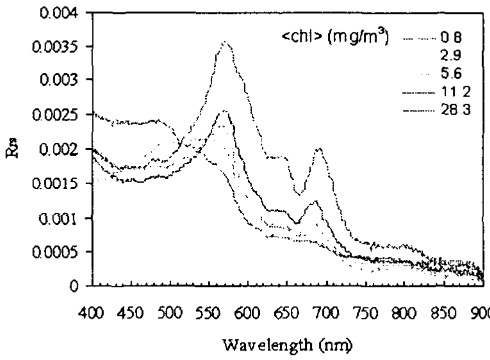


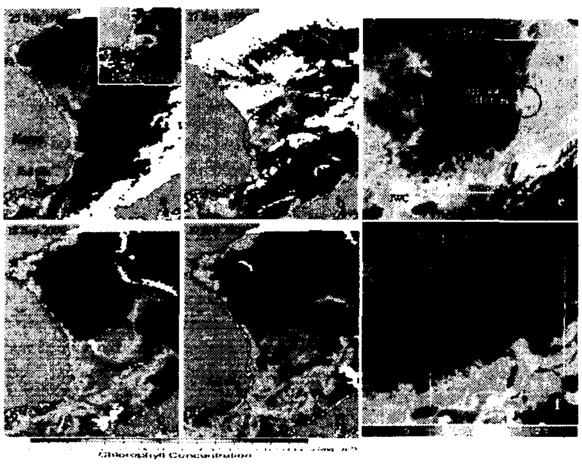
Fig. 3. Example of remote sensing reflectance $R_{rs}(\lambda)$ spectra, corresponding to different Chl-a concentrations 0.8~28.3 mg/m^3, showing absorption maxima at 445nm and reflectance maxima at 567nm and chlorophyll fluorescence peak maxima at 685nm.

3. Results and Discussion

The distribution of Chl-a and SST throughout the Jin-hae Bay and offshore waters is illustrated in Figs. 4a-f, where recurrent patterns of Chl-a concentration with dominant peak ,during September 1998-2000, are apparent in these imageries. In August 1998, *Cochlodinium.p* formed monospecific specific blooms with cell concentrations 1500~ 26000 cells ml^{-1}, which appear to have transformed to the east off the Ulsan coast (attached on top of Fig. 4a). At this time, satellite-derived Chl-a concentration varied from 3~54 mg m^{-3} inside the Jin-hae Bay and 0.6~12.5 outside the Bay. The accumulation of *Cochlodinium.p* and other associated dinoflagellates within the euphotic layer off the Ulsan coast mainly resulted from vertical mixing and active upward transport of nutrients into the well-lit surface layer, which led to the formation of quick eutrophic situations off the Ulsan coast. Satellite observations suggest that the bloom was persistent for more than two months inside the Jin-hae Bay and had a short-term variability with less than a month in the nutrient-rich upwelled waters. Such conditions were encountered in coastal upwelling areas at mid and high latitudes (Glover and Brewer, 1988; Morel and Berthon, 1989). Byun (1989) pointed out that eastward transport and upwelling off the southeastern Korean coasts occurs when propagation of frontal system takes place along the Tsushima Strait during the summer and fall seasons. Observations of salinity and temperature, sampled concurrently with satellite overpass, demonstrate significant differences in these variables during the evolution and physical transport of *Cochlodinium.p* blooms to the east.

On the contrary, *Cochlodinium.p* exhibited recurrent patterns in SeaWiFS-derived Chl-a, extending to the south due to the influence of warm water (TWC) from the Koroshio, as evident in Figs. 4a, b and e. When the in-situ observations confirmed *Cochlodinium.p* abundances, which remained higher (maximum 27000 cells ml^{-1}) inside the Jin-hae Bay, SeaWiFS-derived Chl-a concentration appear to vary from 3~58 mg/m^3 inside the Jin-hae Bay and 2~26 mg/m^3 outside the Bay. It is worth noting that at most of stations, in-situ Chl-a concentration resembled that of satellite measurements except for few locations close to the coast, where it reached at very high levels (comparison was made for the August imageries that are not included here) in some places, indicating patchiness of *Cochlodinium.p*. One should note that the southward migration of *Cochlodinium.p* bloom, originated from low saline and cold water ($\theta<22°C$; $S<32.2$) inside the Jin-hae Bay, led to high Chl-a concentrations offshore the South Sea. CTD survey demonstrates pronounced hydrographic variability at both surface and subsurface, indicating the transportation of thermohaline water of the Kuroshio through the Tsushima Strait, which raised temperature up to 23°C warmer than the surrounding water, as seen in AVHRR-derived SST image (Fig. 4e). The increased temperature and northeastward transportation of Kuroshio waters, which transports ocean nutrients, provide favorable conditions for the rapid growth, evolution and migration of *Cochlodinium.p* blooms towards the northeastward propagation of thermohaline waters off the southern coast (Kim et al., 2004). Tang et al. (2003) mentioned that dinoflagellates blooms extensively with a peak when water temperature increases from 22 to 25°C. It is interesting to see that the southward flow pattern of *Cochlodinium.p* bloom appears to have transformed essentially northeastwardly by the existence of TWC, resulting in a mushroom-like structure of Chl-a concentration 1.5~17 mg m^{-3} (Fig. 4b). On the other hand, a close inspection of the same Chl-a image reveals that *Cochlodinium.p* bloom of longer duration and other dinoflagellates bloom of relatively shorter duration become apparent in nutrient-rich waters off the Yongil and further northern coasts. Perhaps *Cochlodinium.p* bloom was caused by anthropogenic nutrients from the Yongil river, and the other dinoflagellate bloom positioning north of it may be partly due to its ability to grow in upwelled waters formed by the eddy-like feature, which intervened to raise the concentrations of growth-limiting nutrients into the euphotic zone. This event was typically episodic in nature, and energetic enough to cause an injection of essential and limiting nutrients into the euphotic layer, resulting in the enhanced Chl-a concentrations 0.9~2.7 mg m^{-3} (Falkowski et al., 1991; Seki et al., 2001). The eddy-like feature is manifest in SST image and in-situ data (Fig. 4e). The eddy-like feature, that did not trap algal matter like rings, produced upwelling over a time scale sufficiently long to produce a transient bloom at this location and resulted in a spatially diffuse trail like pattern of Chl-a several hundred kilometers from waters north of the Yongil estuary to waters north off Ulleungdo. Trajectory of a satellite-tracked surface drifter (Agros buoy) and hydrographic measurements clearly demonstrate that this pattern was potentially influenced by the propagation of EKWC, which turned anticyclonically in the upper ocean waters north off Ulleungdo with high speed of about 50-60 cm/s as shown in the previous section. As a consequence of this anticyclonic eddy, the waters around the Ulleungdo that are usually characterized to belong to Type-1 waters are often altered to Type-2 waters owing to the accumulation and blooming of dinoflagellates and diatoms by the EKWC and NKCC circulations.

In September 2000, when the monsoonal storms resulted in accretion of large amount of land-based nutrients and pollutants into coastal waters of the South Sea of Korea, *Cochlodinium.p* bloomed extensively with cell concentrations typical of 1000-28000 cells/ml and discolored waters all along the southern coast, causing virtual collapse of ecosystems with accompanying serious economic impacts. Thus, the blooms resulting from complex coupled physical/biological processes strongly affected the optical properties of the southern coastal ocean, including offshore waters, as seen in Fig. 4c, d and f. In fact, it was the first time to document the physical conditions sustaining the rapid growth and extension of *Cochlodinium.p* bloom, typically on the range over 100km on the TWC (S>32.2 and θ>21°C at surface; S>34.4 and θ>15°C at 75dB) and its Offshore Branch towards the southern East Sea. It is worthwhile to recall that the growth rate of *Cochlodinium.p* is maximum of(?) 0.41 day^{-1} at 25°C and salinity 34 according to Kim et al. (2004). We believe that the southward penetration of NKCC waters along the Korean coast had a tendency to result in hampering the escalation of EKWC, giving rise to the strong eastward flow of the Offshore Branch, which directed the spatial structure of *Cochlodinium.p* and other dinoflagellates blooms towards the east. During this period, the advancement of both ESIW and NKCC waters led to the deformation of anticyclonic eddy feature, essentially formed during May 2000, associated with lower salinity and temperature S<33 and θ<15°C. Bloom patterns inside the eddy, possibly constituted mostly of dinoflagellates, was tracked from SeaWiFS imagery, exhibiting Chl-a concentration 0.5~2.1 mg/m^3. In fact, dinoflagellate populations associated with this eddy were much higher during May 2000 than that observed in September 2000 (please see Ahn et al. 2004). Comparing to the September 1999 bloom, it appears that the intensity and spatial extent of the September 2000 bloom increased in relation to the underlying strong physical forcing of the ecosystem. Recent field observations reveal that occurrence of *Cochlodinium.p* bloom remains a recurrent problem in the Jin-hae and adjacent Bays waters (1000~26000 cells/ml in September 2003). Thus, continued monitoring of the distribution and abundance is necessary and will increase our knowledge of the factors influencing the persistence of this bloom and its impact on the ecosystem.



Figs. 4a-f. SeaWiFS-Chl-a and AVHRR-SST images showing the evolution of *Cochlodinium.p* bloom and existence of oceanic warm currents in the South Sea during the period 1998-2000.

4. Conclusion

Significant efforts have been made on the data collected from satellite and in-situ observations to understand the mechanisms underlying the population dynamics of *Cochlodinium.p* blooms of August/September 1999 and 2000 in waters off the Korean coasts. During this period, *Cochlodinium.p* bloomed at higher concentrations (normally from 1000~ 30000 cells ml^{-1}) and discolored waters all along the southern and eastern coasts. Such increased concentrations have been shown to cause negative impacts on aquaculture fish populations (Kim et al., 1994; Kim, 1998) and can be supported by a substantial amount of nutrients derived from the land in summer and fall seasons. Satellite-derived SST and CTD surveys showed elevated water temperature and salinity offshore, which are most important factors, providing favorable conditions for the south- and eastward initiation of *Cochlodinium.p* blooms from the enclosed Bays. Under these highly dynamic hydrographic and blooms conditions, a significant variability in the sun-induced fluorescence signal occurred, which was attributed to changes in the local environmental factors, such as nutrients, temperature and light conditions. From this study, we observed that increased frequency, intensity and spatial extent of *Cochlodinium.p* blooms reveal a potentially important impact on aquaculture fish resources and submerged aquatic vegetation. Thus, additional research and continued monitoring of such harmful algal blooms is necessary for the enhanced understanding and potential prediction of the impact of this bloom on the coastal ocean ecosystem of Korea.

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