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Spatial and Temporal Aspects of Phytoplankton Blooms in Complex Ecosystems Off the Korean Coast from Satellite Ocean Color Observations

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Abstract – Complex physical, chemical and biological interactions off the Korean coast created several striking patterns in the phytoplankton blooms, which became conspicuous during the measurements of ocean color from space. This study concentrated on analyzing the spatial and temporal aspects of phytoplankton chlorophyll variability in these areas using an integrated dataset from a Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Advanced Very High Resolution (AVHRR) sensor, and Conductivity Temperature Depth (CTD) sensor. The results showed that chlorophyll concentrations were elevated in coastal and open ocean regions, with strong summer and fall blooms, which appeared to spread out in most of the enclosed bays and neighboring waters due to certain oceanographic processes. The chlorophyll concentration was observed to range between 3 and 54 mg m^{-3} inside Jin-hae Bay and adjacent coastal bays and 0.5 and 8 mg m^{-3} in the southeast sea offshore waters, this gradual decrease towards oceanic waters suggested physical transports of phytoplankton blooms from the shallow shelves to slope waters through the influence of the Tsushima Warm Current (TWC) along the Tsushima Strait. Horizontal distribution of potential temperature (θ) and salinity (S) of water off the southeastern coast exhibited cold and low saline surface water (θ<19°C; S<32.4) and warm and high saline subsurface water (θ>12°C; S>34.4) at 75dBar, corroborating TWC intrusion along the Tsushima Strait. An eastward branch of this current was called the East Korean Warm Current (EKWC), tracked with the help of CTD data and satellite-derived sea surface temperature, which often influenced the dynamics of mesoscale anticyclonic eddy fields off the Korean east coast during the summer season. The process of such mesoscale anticyclonic eddy features might have produced interior upwelling that could have shoaled and steepened the nutricline, enhancing phytoplankton population by advection or diffusion of nutrients in the vicinity of Ulleungdo in the East Sea.

Key words – remote sensing, complex ecosystem, phytoplankton blooms, upwelling, anticyclonic eddy, SeaWiFS, AVHRR, CTD survey

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1. Introduction

Phytoplankton blooms appear to be an increasingly common phenomena on a worldwide scale, which occur when the rate of phytoplankton growth exceeds the rate of cell dispersion, due to anthropogenic nitrification that alters coastal environments worldwide (Shumway 1990; Burkholder 1998), or steepening of nutricline by the intervenes of physical processes (Falkowski *et al.* 1991; Olaizola *et al.* 1993). The semi-enclosed nature of Korean southeast coastal bays often reaches extremity in the eutrophic state by receiving terrestrial wastewater and pollutants, giving rise to the occurrence and outbreaks of various phytoplankton blooms, including blooms of red tide caused by *Cochlodinium polykrikoides* which have significantly increased in frequency, intensity and geographic distribution and caused massive mortalities of aquaculture fish off the Korean southeastern and eastern coasts, particularly during fall season (Kim *et al.* 1999). Other environmental factors such as warming, resuspension of spores and advection have been observed for the increased occurrence of red tide and non-red tide blooms in the Korean coastal waters (Kim *et al.* 1990).

Summer phytoplankton blooms also occur periodically when the various scales of physical phenomena intervene to raise the concentrations of growth-limiting nutrients into the euphotic layer in the Korean East Sea waters. Examples of such events include mixing and decay of stratification by the passage of warm and cold currents and formation of masoscale eddy features (Falkowski *et al.* 1991; McGillicuddy and Robinson 1997; Chang *et al.* 2002). These phenomena are likely to be significant mechanisms for the transport of large amounts of nutrients to the euphotic zone, resulting in the enhanced phytoplankton populations observed from satellite ocean color observations in the East Sea. The relationship between physical mechanisms and phytoplankton blooms of this region has yet to be understood, because there have been no reports of the phytoplankton bloom established with reference to these physical processes.

Because of the high temporal and spatial heterogeneity of oceanic ecosystem and processes as well as the expense and limited range of research vessels, monitoring of coastal and offshore blooms with traditional field sampling at few stations remains critical, therefore the only effective way of monitoring such large areas on a regular basis is through remote sensing. Utilization of remote sensing technology because of its synoptic and repeat coverage has been explored for detecting algal blooms, delineating their spatial extent, addressing their impacts as well as describing the associated hydrographic conditions (Haddad 1982; Cullen *et al.* 1997; Tester and Stumpf 1998; Schofield *et al.* 1999). Steidinger and Haddad (1981) were among the first to demonstrate the potential of satellite ocean color sensors with Coastal Zone Color Scanner (CZCS) for the detection of a major *Karenia brevis* bloom in western Florida waters. With the availability of daily imagery from the current SeaWiFS operational ocean color sensor, routine monitoring has been initiated by Stumpf (2001), indicating that the use of chlorophyll data might provide a means for the detection of phytoplankton blooms in oceanic waters. Similarly, Chang *et al.* (2001) explored the usefulness of SeaWiFS ocean color imagery for detecting and monitoring of *Gymnodinium catenatum* blooms in New Zealand waters. On the other hand, sea surface temperature measurements by Advanced Very High Resolution Radiometer (AVHRR) sensors on National Oceanic and Atmospheric Administration (NOAA) satellites, which provide real-time capability with two thermal infrared channels, have been found to be useful for the derivation of circulation patterns, structure of oceanic fronts, behavior of eddies/meanders and the location of upwelling zones and associated chemical and biological features (Pearce and Pattiaratchi 1997; Cipollini *et al.* 1998; Chang *et al.* 2002; Tang *et al.* 2003).

In this paper, we present the analysis of the spatial and temporal variability of summer and fall phytoplankton blooms off the Korean southeastern and eastern coasts using the combined data sets of satellite ocean color and sea surface temperature, and in-situ bio-optical and hydrographic observations.

2. Materials and Methods

Study area and cruise measurements

The study area includes optically complex waters off the Korean southeastern and eastern coasts. Shallow waters with a depth of less than 60 m, connecting to the East China Sea (ECS) in the southwest and East Sea (ES) in the northeast, characterize the southeastern coastal sea, whereas deep waters with a mean depth of 1543 m, with subtropical and subarctic circulations bounded by the subarctic fronts, characterize the East Sea. Detailed regional surface current patterns of these regions and locations of frequent phytoplankton blooms (in the enclosed circles) are illustrated in Figs. 1a and b. The well-known oceanic current in the southeast sea is the Tsushima Warm Current (TWC), which transports nutrient-abundant Kuroshio waters into the East Sea through Tsushima Strait. This current splits into two distinct branches, one flowing northward along the Korean east coast called the East Korean Warm Current (EKWC), and another flowing along the Japanese coast called the Offshore Branch (OB) (Chang *et al.* 2002). The northward flow of EKWC is regarded as sub-tropical circulation (Yoon 1982), while the counterpart of the Liman Cold Current (LCC) flowing southwestward along the Russian coast and southward along the North Korean coast is regarded as subarctic circulation in the East Sea. These circulations result in several small and mesoscale eddies that constitute dinoflagellates and diatoms blooms, especially in the summer and fall seasons (Kim *et al.* 1997; Senjyu 1999).

In-situ bio-optical measurements were performed during four cruises (onboard R/V Olympic) conducted over the Jin-hae Bay and neighboring waters through the years 1998-2003. All these cruises coincided with the rapid growth and development of *Cochlodinium.p* blooms in August/September. The ship surveys consisted of over 200 stations inside and outside the blooms. During each cruise, water samples were collected and subsamples of 100-1000 ml to measure chlorophyll (Chl) and SS concentrations were filtered onboard onto a Glass Fiber Filter (GF/F) 25 mm in diameter. The Chl was extracted via the methanol-extraction method and measured using a Perkin-Elmer Lambda 19 dual-beam spectrophotometer (Ahn *et al.* 2001). The absorption spectra of total particulate matter $a_{tot}(\lambda)$ collected onto glass-fiber filters were determined by a wet-filter technique and the absorption spectra of non-algal particles $a_{non}(\lambda)$, determined by a chemical extraction method (Kishino *et al.* 1984), was subtracted with $a_{tot}(\lambda)$ to derive the absorption spectra of phytoplankton $a_{ph}(\lambda)$.

Simultaneously, radiometric measurements such as downward spectral irradiance ($E_d(\lambda)$) and total water leaving radiance ($tL_w(\lambda)$) and sky radiance ($L_{sky}(\lambda)$) were performed at various sample sites using a dual field spectroradiometer (ASD Inc.) with a spectral range between 350-1050 nm and a spectral sample interval of 1.4 nm. The data recorded in units of mW cm^{-2} μm^{-1} sr^{-1} needed to be corrected for the contribution of skylight reflection and air-sea interface effects (Ahn *et al.* 2001). Thus, the total measured water leaving radiance ($tL_w(\lambda)$) was corrected for the sky light reflection and the air-sea interface effects using the equation $L_w(\lambda)=tL_w(\lambda)-F_r(\lambda)\times L_{sky}(\lambda)$. The values

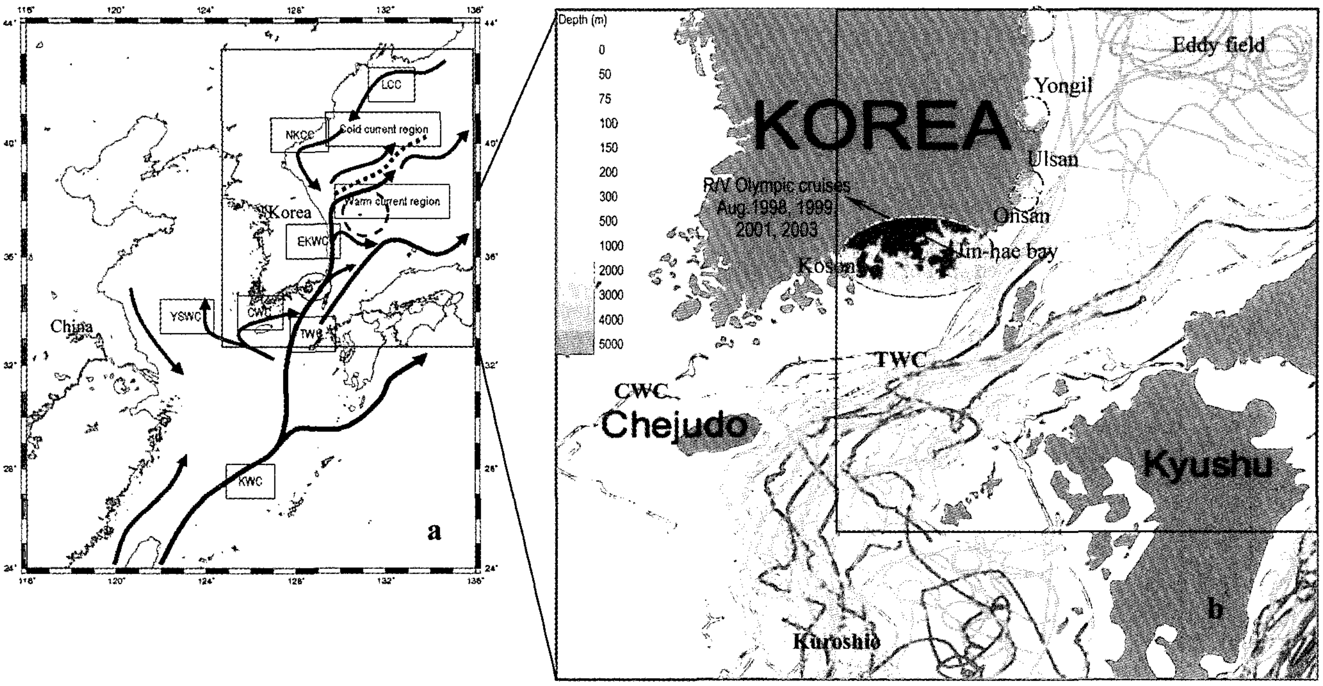


Fig. 1. (**a**) Schematic representation of regional patterns of surface currents responsible for various physical and biological dynamics in Korean and adjacent seas. KWC-Kuroshio Warm Current; TWC-Tsushima Warm Current; YSWC- Yellow Sea Warm Current; CWC-Cheju Warm Current; EKWC-East Korean Warm Current; NKWC-North Korean Cold Current; LCC-Liman Cold Current. (**b**) General patterns in sea surface current field observed from the satellite-tracked drifter trajectories in the South Sea during 1989 to 1996 (Lie *et al.* 1998). The shaded circles represent the areas of harmful *Cocholodinium.p* bloom occurrences off the Korean southeastern and eastern coasts, while the arrow mark denotes the areas of in-situ measurements carried out in these waters.

of $L_{sky}(\lambda)$ were obtained from the sky radiometer and F_r value was assumed to be constant 0.025 (Austin 1974). In fact, F_r varies with viewing geometry, sky conditions (clear, partially and densely cloudy) and sea surface roughness due to wind and is wavelength-dependent under a cloudy sky (Mobley 1999). The remote sensing reflectance was then obtained by normalizing corrected water-leaving radiance $L_w(\lambda)$ to downwelling irradiance (E_d) as follows, $R_{rs}(0^+\lambda) = L_w(\lambda)/E_d(0^+\lambda)$.

In September 1999 and May 2000 when massive phytoplankton blooms occurred off the Korean southeastern and eastern coasts, CTD surveys (Sea Cat Profiler, Sea-Bird Electronics) were performed aboard the R/V EARDO to elucidate detailed hydrographic conditions that sustained the formation of these blooms. Vertical sampling was made with CTD lowered to 500 dBar at most of the stations (total 75 stations). Accuracy of SBE 911 CTD is ±0.001 °C in temperature and ±0.0015 in salinity with their respective resolutions of 0.0002 °C and 0.0004 (Chang *et al.* 2002). Both the CTD data and satellite-derived (AVHRR) sea surface temperature (SST) taken at the time of each CTD survey provided a complete overview of the prevailing hydrography and phytoplankton bloom dynamics off the Korean southeastern and eastern coasts.

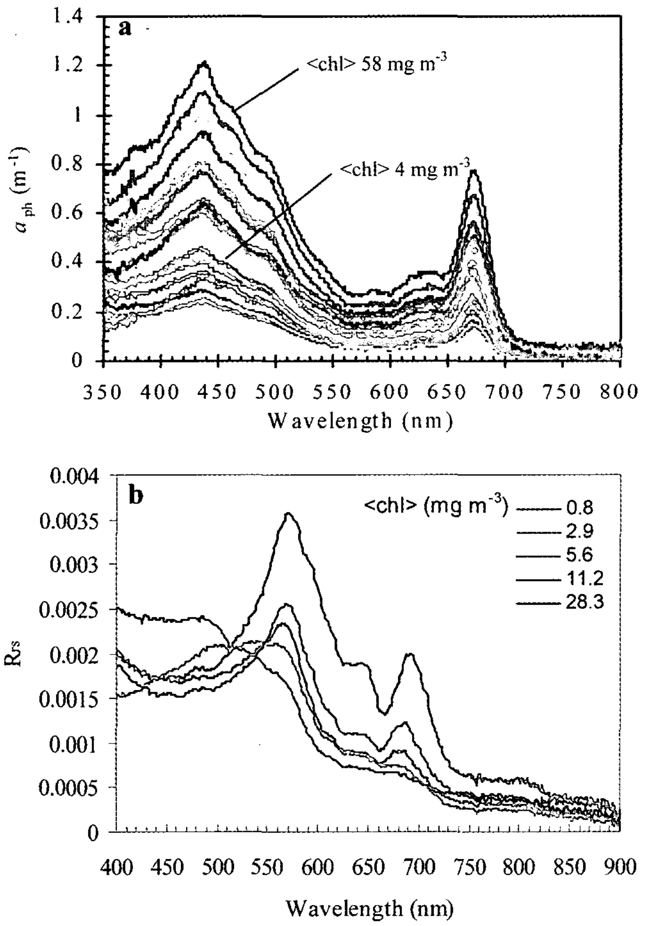
Satellite imagery and processing

Level 1A local area coverage SeaWiFS imageries were collected from the KORDI satellite data receiving station for the periods 1998 to 2000. The ocean color radiances were atmospherically corrected and processed to level 2 using NASA SeaDAS version 4.4 (Tomlinson *et al.* 2004), which has an updated atmospheric correction algorithm that compensates for near-infrared water-leaving radiance and for absorbing aerosols (Stumpf *et al.* 2003). Surface chlorophyll-a (Chl-a) concentrations were then derived from the atmospherically corrected SeaWiFS data using the NASA OC4v4 bio-optical algorithm (Hooker and Firestone 2000) within SeaDAS. The SeaWiFS-derived Chl-a calculated using the OC4v4 bio-optical algorithm appeared to be nearly consistent with the in-situ Chl-a measured in red tide and clear waters. Similarly, AVHRR infrared imagery collected from KORDI data receiving station were geo-referenced to a common grid and projection system at a spatial resolution of 1.1km, and land pixels were subjected to masking to a single value. Sea surface temperature was then estimated by combining the radiance temperatures derived from the two individual thermal bands to account for the varying amounts of water vapor in the atmosphere (Barton 1995). This was accomplished using the split window MCSST (Multi Channel Sea Surface Temperature) dual channel algorithm (available with TerraScan software), which was found efficient for accurate SST computation, with the root mean square differences of about 0.6 °C (Li et al. 2001).

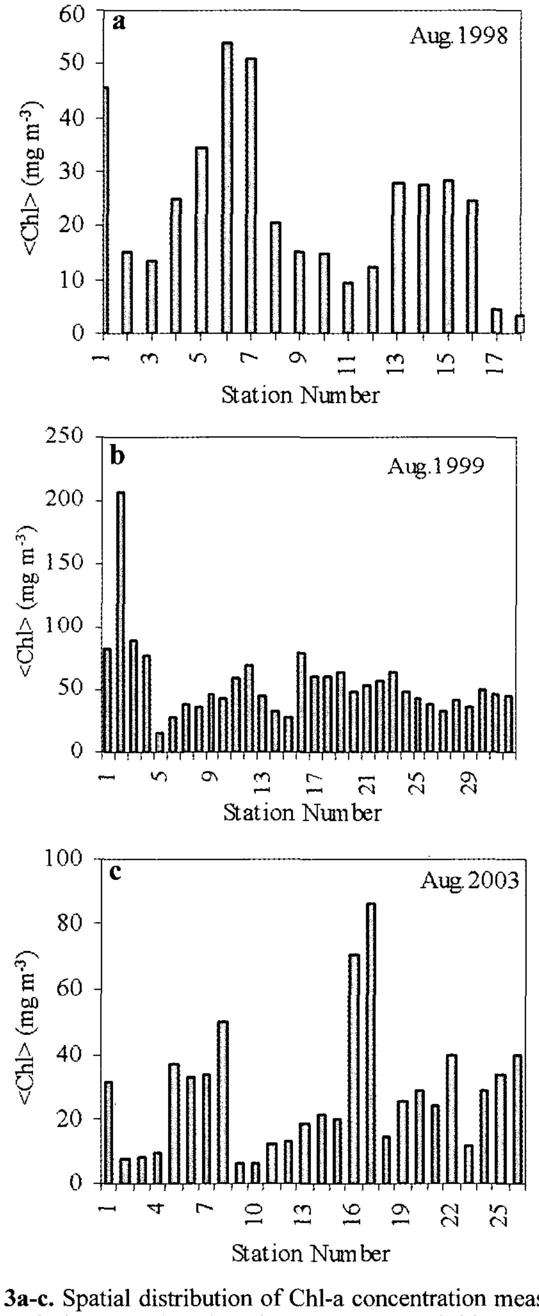
3. Results and Discussion

Bio-optical measurements during August/September

Figs. 2a and b show examples of $a_{ph}(\lambda)$ and $R_{rs}(\lambda)$ spectra measured in the red tide waters of Jin-hae Bay during August 1999. The magnitude of absorption spectra of phytoplankton measured in these waters appear to have increased with the increase in Chl-*a* concentrations, and two dominant absorption peaks can be detected around 443 nm and 670 nm. Ahn and Moon (1999) observed large variations in $a_{ph}(\lambda)$ spectral values in areas with dense algal matter in Jin-hae and GeoJea-Do bays and less variations in areas with less dense algal matters associated with the East Sea and Yellow Sea. Sources of variability in phytoplankton spectral absorption might result from physiological differences, pigment composition, cellular organization and package effect. The example of remote sensing reflectance $R_{rs}(\lambda)$ spectra corresponding to



Figs. 2a and b. Absorption spectra $a_{ph}(\lambda)$ observed in the Jin-hae Bay red tide waters exhibiting two absorption features around 444 nm and 670 nm (a), and example of remote sensing reflectance $R_{rs}(\lambda)$ spectra, corresponding to different chlorophyll concentrations 0.8~28.3 mg m^{-3}, showing absorption maxima at 445 nm and reflectance maxima at 567 nm and chlorophyll fluorescence peak maxima at 685 nm (b).



Figs. 3a-c. Spatial distribution of Chl-a concentration measured during the R/V Olympic cruises over red tide waters of Jin-hae Bay (1998-2003). At most of the stations, higher Chl-a concentrations are observed to be representative of massive blooms during these periods.

chlorophyll concentrations 0.8~28.3 mg m^{-3} show the absorption maxima at 445 nm and reflectance maxima at 567 nm and sun-induced chlorophyll fluorescence peak maxima around 685 nm (Fig. 2b). Note that when Chl-*a* concentration increases, the magnitude of the fluorescence peak increases with a notable decrease towards the red part of the spectrum, providing a possibility of estimating chlorophyll concentration using a bio-optical algorithm based on this signal. Figs. 3a-c display chlorophyll concentrations measured in Jin-hae Bay and neighboring waters during August/September through the years 1998-2003. In most of the stations, chlorophyll concentrations were elevated throughout all these times with phytoplankton blooms superimposed, *i.e.*, it varied from 1.5 to 30 mg m^{-3} around the coastal bays, except for a few locations close to the coast where it often exceeded 50 mg m^{-3}.

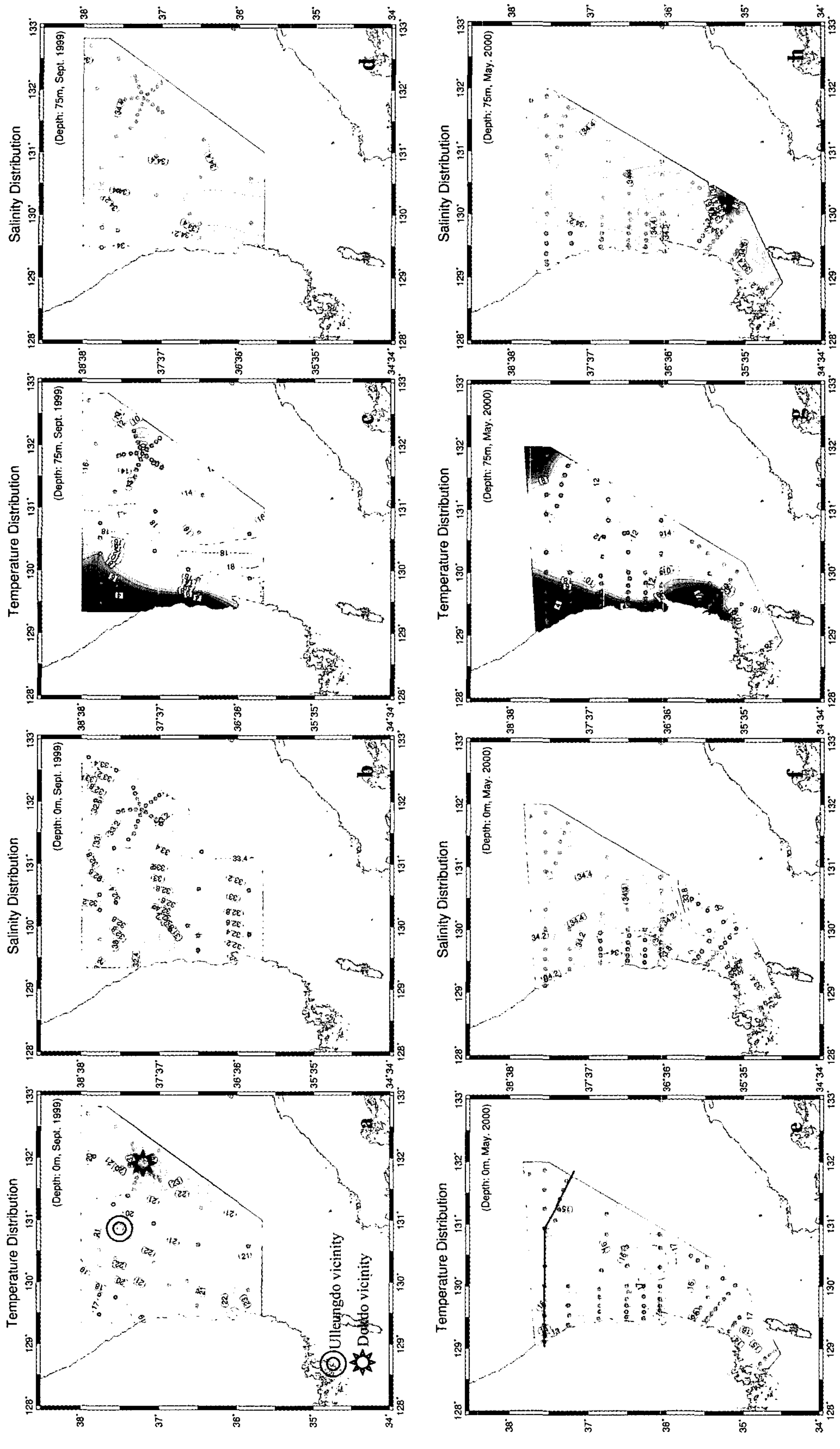
Hydrographic survey during September 1999

Conductivity, temperature and depth (CTD) profiles made at discrete locations off the Korean southeastern and eastern coasts were analyzed to elucidate the physical consequences on the initiation and movements of phytoplankton blooms in the shallow shelf and deep oceanic waters. The continuous temperature and salinity profiles obtained with CTD exhibited low temperature (θ) 23°C and salinity (S) < 32.2 of surface waters around the southeast coastal areas (not shown) and Ulsan coastal areas, with a rapid increase in these fields in the southeast sea offshore, indicative of the northeastward intrusion of TWC along the Tsushima Strait (Figs. 4a and b). The cold and low saline waters might be from river discharges along the southern coastal regions and water masses of the Yangtze River estuary of the East China Sea, particularly in summer and fall seasons (Kim *et al.* 1991; Chang *et al.* 2000). The East Korean Warm Current (EKWC) flowing along the Korean east coast appeared to cut off from the coast around 36.6°N, resulting in the formation of smaller scale eddy-like features to the north off the coast of Pohang. The remainder of this current passing through the Ulleung Interplain Gap east at about 40°N led to a larger scale eddy turned anticyclonically in an area north of Ulleungdo (Fig. 4a). The trajectory of the satellite-tracked surface drifter (Agros buoy) gave a special insight into this eddy with a high speed of about 50-60 cm s^{-1}. This anticyclonic warm eddy draws Liman cold water north of the subpolar front to the southwest, producing water masses with very different physical, biological, and optical properties of the East Sea during the summer and fall seasons. These waters characterized by a greater supply of nutrients from the subsurface nutrient pool might constitute more favorable regions for promoting phytoplankton blooms off the Korean east coast (Suh *et al.* 1999). Concurrent measurements of hydrographic features at subsurface waters (at 75 dBar) showed two distinctive waters masses, the warm and high saline water (θ>17 and S>34.4) in the vicinity of Tsushima Strait and southwestern area of the East Sea, and cold and low saline water (θ<14 and S<34.3) off the southeastern and eastern coasts, which occurred due to the influence of TWC and EKWC along the east coast (Figs. 4c and d).

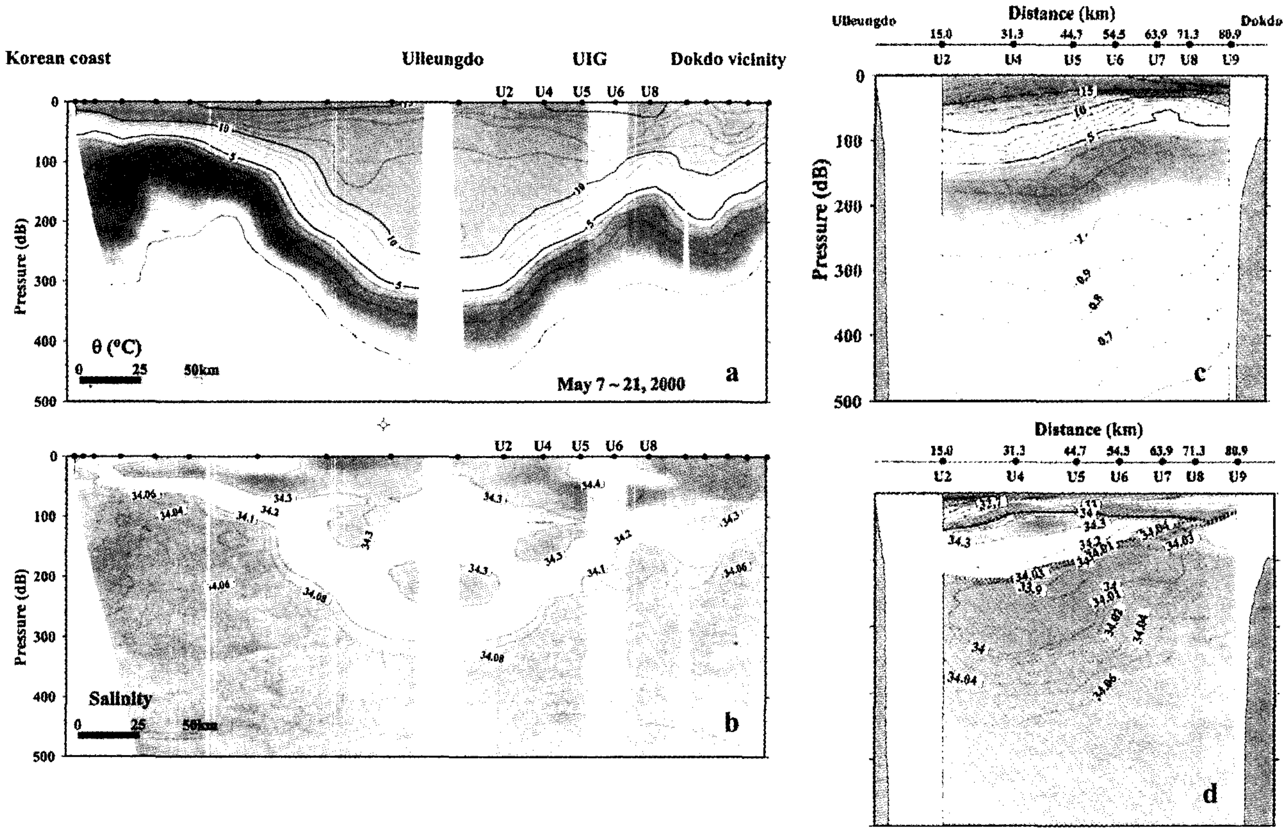
Hydrographic survey during May and September 2000

CTD surveys on two occasions, May and September 2000, were also performed over the same regions to demonstrate variations in hydrographic features, related to the development of summer and fall phytoplankton blooms off the Korean coasts. In Figs. 4e and f, temperature and salinity of surface water exhibited two water masses with distinct boundaries: cold and high saline water (θ<15°C; S>33.8) associated with the southern coastal areas and warm and relatively low saline water (θ>16°C; S<33.2) associated with the southeast sea offshore. The formation of warm and low saline water of the upper layer has been suggested as a possible influence on the water mass characteristics west of Jeju-do (Kim *et al.* 1991). At 75 dBar, there existed rapid changes in these water mass characteristics owing to the thermohaline front along 128.5°E-130°E with a water mass of θ>15°C and S>34.5 (Figs. 4g and h). Hydrographic measurements of the surface waters further displayed TWC around 35°N and 129.5°E, splitting EKWC and OB. The northward flow of EKWC bifurcated at 38°N and formed an intensive anticyclonic eddy around Ulleungdo, which is referred to as Ulleung Warm Eddy (UWE) after Chang *et al.* (2002). The broad temperature and salinity distribution contour lines (θ~16°C; S<34.4) in the vicinity of Ullenungdo, showed signs of this eddy formation around Ulleungdo (Figs. 4g and h). To understand the behavior of this eddy in the subsurface water column, vertical profiles of temperature and salinity were made along the transect between the Korean east coast and Dokdo in the East Sea and revealed that a homogeneous thermostad developed vertically close to Ulleungdo and isoclines slope, which had moved upwards to Dokdo, with an isotherm in the lower boundary of the UWE (up to 250 dBar), with θ=10°C and S=34.3 (Figs. 5a and b) (Chang *et al.* 2002). The temperature below this isotherm remained colder (θ<5°C) and extended to the east off Dokdo and west off the Korean coast. High salinity S=34.4 of surface water occurred in the periphery of the eddy close to Dokdo.

In September 2000, CTD observations intersected the summer-eddy and revealed isotherms and a high salinity core, noticeable with the thermostad capped by surface warm and low salinity water (θ>15°C; S<33) (Figs. 5c and d) (Chang *et al.* 2002). The prevailing water mass characteristics during this period suggested that the



Figs. 4a-h. CTD measurements show horizontal distribution of potential temperature (θ) and salinity at surface and 75 dBar in September 1999 (a-d) and May 2000 (e-h).



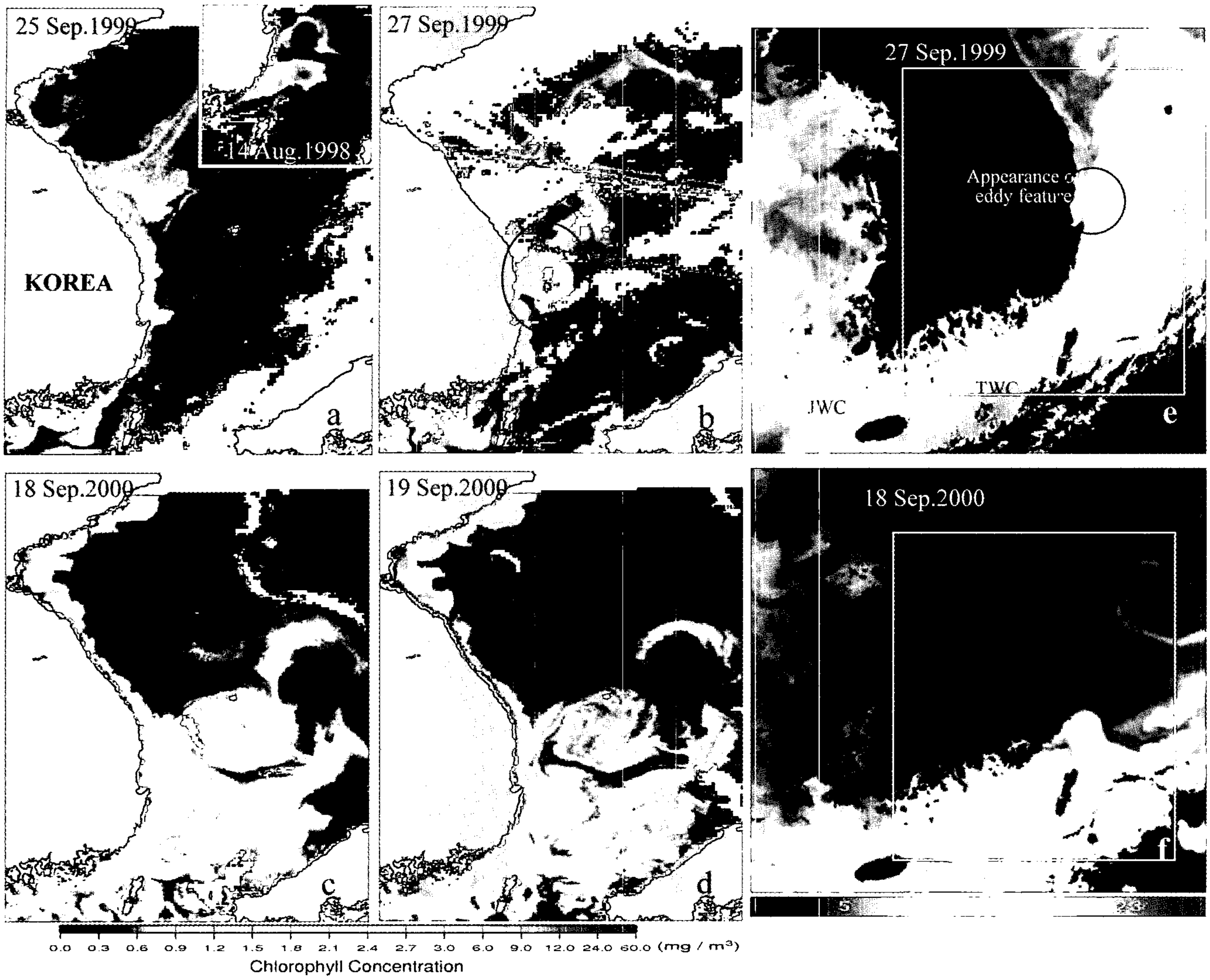
Figs. 5a-d. CTD surveys performed along a section between the Korean east coast to Dokdo vicinity during May 2000 show vertical distribution of potential temperature (θ) and salinity, caused by an anticyclonic eddy feature in the East Sea (a and b). A similar survey performed between Ulleungdo and Dokdo vicinity in September 2000 indicates surface warming and low saline waters. These illustrations are from Chang *et al.* (2002).

structure of this eddy feature appears to have spatially shrunken as a result of the domination of low salinity surface waters and NKCW (Kim *et al.* 1991; Cho and Kim 1994). Because of the southward penetration of the cold phase that hampered the escalation of the EKWC, the 10°C isotherm positioned at 220 dBar (at station just west off Ulleungdo) during May 2000 was apparently reduced to 80dBar in September 2000, indicative of the decay of this eddy structure in the vicinity of Ulleungdo. The weakening of EKWC gave rise to the strong eastward flow of the Offshore Branch (OB), as manifest in Chl-a and SST images.

Distribution of chlorophyll during september

The distribution of Chl-a and SST throughout the Jin-hae Bay and offshore waters is displayed in Figs. 6a-f, where recurrent patterns of Chl-a concentration with dominant peaks during September 1998-2000 are conspicuous in these images. In August 1998, large phytoplankton blooms, probably formed by *Cochlodinium.p*, appear to have moved eastward off the Ulsan coast (see the attached picture on the top right corner of Fig. 6a). During this time, SeaWiFS-derived Chl-a concentration varied from 3-54 mg m^{-3} inside the Jin-hae Bay and 0.5~6 outside the bay. The eastward movement and accumulation of phytoplankton species within the euphotic layer off the Ulsan coast might be caused by upwelling, which brought nutrient-abundant subsurface waters to the surface layers, leading to produce quick eutrophic situations off the Ulsan coast. Time series of SeaWiFS-derived Chl-a suggested that the bloom was persistent for more than two months inside Jin-hae Bay and over a period of shorter duration (about two weeks) in the nutrient-rich upwelled waters. Previously, upwelling-induced phytoplankton blooms have been reported in other coastal waters such as Taiwan Strait (Li 1993; Tang *et al.* 2002) and at mid and high latitudes (Glover and Brewer 1988; Morel and Berthon 1989). Comprehensive studies of the southeast sea hydrography related eastward transport of phytoplankton blooms to the propagation of a frontal system along the Tsushima Strait (Byun 1989).

In September 1999, SeaWiFS-derived Chl-a exhibited



Figs. 6a-f. Spatial and temporal aspects of surface chlorophyll concentrations analyzed from the SeaWiFS ocean color imagery, showing recurrent patterns of phytoplankton blooms (a-d), caused by several physical mechanisms manifest in the AVHRR SST images (e and f).

recurrent patterns of *Cochlodinium.p* blooms, associated with the frontal system formed by TWC along the Tsushima Strait (Figs. 6a, b and e). The formation of a frontal system that could be inferred from the largest gradient of SST measurements (11-24°C) through a NOAA satellite ranged in a horizontal linear and curved extent from several hundreds of kilometers, changing the property of the water in terms of temperature, salinity, macro- and micro- nutrients and density. However, studies are left with less clear physical mechanisms involved in the formation of phytoplankton blooms associated with this front. Our in-situ observations confirmed the initiation of these blooms in August 1999. SeaWiFS-derived Chl-a concentrations over the Jin-hae Bay waters increased from 3-52 mg m^{-3}. The southward extension of phytoplankton blooms that originally resulted from low saline and cold water ($\theta<14$ and $S<34.3$) around Jin-hae Bay and Geoje Island apparently increased SeaWiFS-derived Chl-a concentrations to range between 1-8 mg m^{-3} in slightly warm and high saline waters induced by TWC offshore. Findings of previous studies support the idea that warming and a slightly eutrophic environment is optimal for the occurrence of the highest phytoplankton concentrations that often convert the bloom into a mono-specific state (Tang *et al.* 2003; Kim *et al.* 2004). Examination of Chl-a imagery further revealed that the southward extension of these blooms tended to move northeastward as a result of TWC intrusion, resulting in a mushroom-like structure with Chl-a ranging between 1.5-17 mg m^{-3} (Fig. 6b).

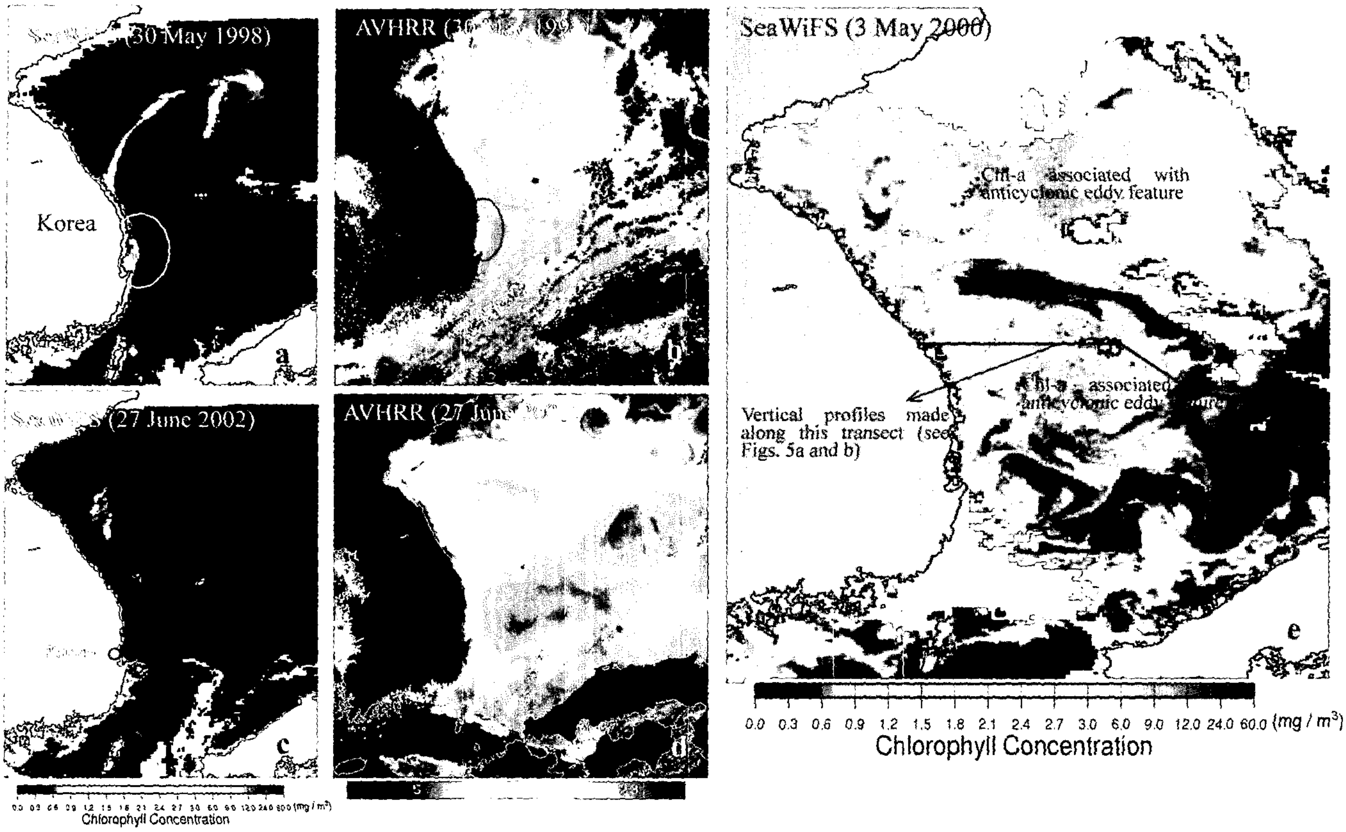
In contrast, dense phytoplankton booms occurred around the Yongil estuary, spanning more than 6 weeks and spreading in the neighboring ocean waters as seen in Fig. 6b. The occurrence of these blooms might be caused by anthropogenic nutrification due to the Yongil River, while another bloom of shorter duration north of the Yongil estuary might be owing to the intervening of eddy-like features off the Korean east coast. 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 algal biomass, which produced Chl-a concentrations 0.9~2.7 mg m^{-3}, as previously observed by Falkowski *et al.* (1991). The eddy-like feature that is manifest in SST image (Fig. 6e) 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 that extended 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 demonstrated that this pattern was formed as the consequence of EKWC that produced anticyclonic circulation of water mass around Ulleungdo at a speed of about 50-60 cm/s.

In September 2000, when the monsoonal storms prevailed, a large discharge of water carrying land-based nutrients and pollutants occurred in the southeast sea coastal areas, which in turn produced massive phytoplankton blooms, probably by *Cochlodinium.p*, discoloring waters all along the southeastern coastal areas and offshore, and posing a potential threat to aquaculture fishery production and other marine organisms. These blooms, resulting from complex coupled physical-chemical and biological processes, strongly affected the optical properties of both the coastal and offshore waters as seen in Fig. 6c, d and f. In fact, this was the first time such massive blooms directed on the Offshore Branch (OB) of TWC (S>32.2 and θ>21°C at surface; S>34.4 and θ>15°C at 75 dBar) were detected over an expanse stretching 100 km along the Japanese coast. During this period, the southward penetration of NKCC water along the Korean coast hampered the escalation of EKWC, giving rise to the strong eastward flow of the Offshore Branch, which directed the spatial structure of these blooms to the southern East Sea (Figs. 6d and f). As a result of NKCC waters, a previously formed anticyclonic eddy feature in May 2000 appeared to be dominated by waters of lower salinity and temperature S<33 and θ<15°C (Figs. 5c and d), and consequently SeaWiFS-derived Chl-a inside the eddy feature south off Ulleungdo was apparently very low 0.5~2.1 mg m^{-3} compared to that observed in May 2000.

Distribution of chlorophyll during May

Several striking patterns in physical and biological properties of the East Sea, tracked with satellite ocean color and infrared observations, are displayed in Figs. 7a-e. Higher Chl-a concentrations are observed along the frontal zone created by EKWC (Figs. 7a and b), thought to result from populations of various dinoflagellates and possibly diatoms that have been reported to be the most dominant bloom forming species in these regions (Lebedev 1968; Orlova *et al.* 1998; Lee *et al.* 1999). SeaWiFS-derived Chl-a and AVHRR-derived SST of the period May 1998 and June 2002 show very interesting patterns in the blooms that evolving from Pohang and neighboring coastal waters appeared to be dominating the East Sea and revealed important information about the anticyclonic eddy features off the Korean east coast. Repeat measurements of hydrographic parameters performed at several locations showed the properties of this eddy as a result of strong northeastward flow of EKWC during summer and weaker flow in the other periods. Warm water flow which induced large changes in the upper ocean biological properties, differed from the surrounding water mass with Chl-a concentrations of 2~21 mg m^{-3} in coastal waters and concentrations of 0.5~2.4 mg m^{-3} in the frontal zone and eddy-induced waters (Figs. 7a and c).

In May 2000, physical and biological samplings of this anticyclonic eddy were carried out in the East Sea waters around Ulleungdo. It was during this period that R/V EARDO cruise track intersected the eddy's centre and the above measurements were made, reflecting the presence of the eddy. SeaWiFS-derived Chl-a concentrations at stations inside the eddy apparently were elevated with the bloom (2-8 mg m^{-3}), while it was <0.5 mg m^{-3} outside the eddy, typical for oligotrophic waters (Fig. 7e). The elevated Chl-a concentrations accompanying the euphotic zone depth that was displaced upwards inside the eddy by enhanced concentrations of dinoflagellates and diatoms populations. Suh *et al.* (1999) observed such elevated Chl-a concentrations associated with this eddy, while Pinca and Dallot (1997) show evidence of a strong predominance of phytoplankton species connected to the anticyclonic eddy features of these regions. In contrast to the cyclonic eddies that have been shown to raise essential nutrients into the euphotic layer, the analogy with oligotrophic gyres would suggest that anticyclonic eddies should be regions of lowered phytoplankton biomasses, but Fig. 7e demonstrated high Chl-a inside the eddy that may be linked to the process of intensive mixing during the formation of anticyclonic eddies that produce interior upwelling, which shoals and steepens nutricline, enhancing production by advection or diffusion of nutrients (Nelson *et al.* 1989). Hydrographic measurements from the CTD survey revealed that the surface water inside the eddy was warmer and saltier than water outside the eddy (Figs. 4e and f) and exhibited the surface mixed layer with a steady



Figs. 7a-e. SeaWiFS-derived chlorophyll shows recurrent patterns of phytoplankton blooms associated with the formation of anticyclonic eddies in the East Sea, indicated in the AVHRR-SST image.

temperature and salinity down to the depth of 250dBar in the vicinity of Ulleungdo (Figs. 5a and b). During this period, occurrences of colossal blooms associated with numerous eddy features, induced by NKCC and LCC waters in the northern part of the East Sea, are manifest in the SeaWiFS-derived Chl-a image, which exhibited higher Chl-a concentrations dominated by populations of diatoms and dionoflagellates (Lebedev 1968; Orlova *et al.* 1998) (Fig. 7e). There was no data of hydrography or nutrients corroborating the actual mechanisms affecting these blooms.

4. Conclusions

We presented analysis of spatial and temporal variability of summer and fall phytoplankton blooms using in-situ and satellite data. SeaWiFS-derived chlorophyll during August/September provided a synoptic overview of the recurrent patterns of massive phytoplankton blooms that discolored waters all along the southeastern coastal areas during fall season, these fall phytoplankton blooms might be the result of coupled coastal and oceanic processes. Though there was no data of nutrients to support our hypothesis, we believe that anthropogenic nitrification gave rise to the coastal blooms around Jin-hae Bay and neighboring waters, and oceanic warm currents offshore set up favorable environmental conditions for the rapid growth and cross shelf transportation of these blooms. The existence of oceanic warm currents and eddy-like features off the Korean southern and eastern coasts were manifest in the satellite-derived sea surface temperature images and CTD profiles acquired from these regions. During summer, in-situ and satellite observations clearly showed that mesoscale perturbations to the water column, associated with the formation of anticyclonic eddy features, caused changes in fertility within the eddy, the perturbations were closely linked to the passage of EKWC and caused the accumulation of a phytoplankton biomass near the surface inside the eddy features. Satellite-derived SST was compatible with CTD observations elucidating physical mechanisms and depicting mesoscale circulation patterns in these regions. We hypothesize that high biomass accumulation observed inside the eddy was likely due to the result of the increased growth rate of phytoplankton, supported by enhanced levels of nutrients and light availability. Sources of nutrients that could sustain the formation of summer blooms in the East Sea might result from intensive mixing and steepening of nutricline through the process of interior upwelling and diffusion produced by the formation of anticyclonic eddies near the Ulleungdo. Massive blooms associated with numerous eddy features in the northwestern part of the East Sea, likely due to the distribution of nutrient-rich North Korean cold waters to this region.

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