Ocean Science Journal, Vol. 41 No. 3, 181-189(2006)

Note

Ocean Science Journal

http://osj.kordi.re.kr

Spring Phytoplankton Bloom in the Fronts of the East China Sea

SeungHyun Son[1]*, Sinjae Yoo[2], and Jae-Hoon Noh[2]

[1]*School of Marine Sciences, University of Maine, Orono, ME 04469, USA*

[2]*Marine Environment Research Department, KORDI, Ansan P.O. Box 29, Seoul 425-600, Korea*

Received 24 August 2006; Revised 11 September 2006; Accepted 26 September 2006

Abstract – Frontal areas between warm and saline waters of the Kuroshio currents and colder and diluted waters of the East China Sea (ECS) influenced by the Changjiang River were identified from the satellite thermal imagery and hydrological data obtained from the Coastal Ocean Process Experiment (COPEX) cruise during the period between March 1st and 10th, 1997. High chlorophyll concentrations appeared in the fronts of the East China Seas with the highest chlorophyll-a concentration in the southwestern area of Jeju Island (~2.9 mg/m^3) and the eastern area of the Changjiang River Mouth (~2.8 mg/m^3). Vertical structures of temperature, salinity and density were similar, showing the fronts between ECS and Kuroshio waters. The water column was well mixed in the shelf waters and was stratified around the fronts. It is inferred that the optimal condition for light utilization and nutrients induced both from the coastal and deep waters enhances the high phytoplankton productivity in the fronts of the ECS. In addition, the high chlorophyll-a in the fronts seems to have been associated with the water column stability as well.

Key words – Spring phytoplankton bloom, fronts, East China Sea, Stratification

1. Introduction

The East China Sea (ECS) is a marginal sea strongly influenced by discharges of fresh water from the Changjiang (Yangtze) River, which is the largest river in Asia. The Kuroshio Current flows northeastward along the continental shelf margin of the ECS at water depths of 200 to 1000 m. The Kuroshio has been known to have two branch currents entering the continental shelf of the ECS: the Taiwan Current (TC) in the southwestern ECS and the Tsushima Warm Currents (TWC) in the southeastern ECS (Beardsley *et al.* 1985). These branch currents are characterized by comparatively high temperature and saline waters. The warm and saline waters meet the diluted ECS waters influenced by the Changjiang River and they form fronts in the ECS (Chen *et al.* 1994). The fronts in the Yellow and East China Seas have been studied with thermal satellite imagery (Zheng and Klemas 1982; Hickox, *et al.* 2000).

Ocean fronts are considered as regions of higher biological productivity (Pingree *et al.* 1976; Fournier *et al.* 1984; Takeoka *et al.* 1993). Optimal conditions for nutrients and light, which enhance phytoplankton productivity, can be achieved in the frontal regions. However, there have been few studies of biological production in the fronts of the East China Sea (Fei 1991; Choi *et al.* 1995; Wu *et al.* 1995). Fei (1991) observed that high chlorophyll-a exists at 20-50 m depth on the shelf side of the Kuroshio front in the continental shelf edge waters of the ECS, showing that the high chlorophyll-a in the area is closely related with the Kuroshio front. High chlorophyll-a has also been found in the region between the Changjiang River Diluted Water and the Yellow Sea Water (Wu *et al.* 1995). Choi *et al.* (1995) have reported that higher values of chlorophyll-a and primary production were found in tidal front areas between coastal waters and offshore waters of the northern ECS.

Spring phytoplankton blooms in the mid-latitude oceans are associated with the water column stability and light limitation based on Sverdrup's hypothesis (Sverdrup 1953). The spring bloom may occur as critical depth, the depth

---

*Corresponding author. E-mail: oceancolor.son@gmail.com in which phytoplankton production vertically integrated from the surface equals the vertically integrated respiration, deepens due to increase of light, while the mixed layer depth shallows (shifts to shallower levels) due to the strong stratification of the water column caused by increasing heat flux. Some studies have focused on the relationship of water column stability to phytoplankton chlorophyll-a distribution (Jones and Gowen 1990; Moline 1998; Agusti and Duarte 1999).

Here, we confirm the location of fronts in the East China Sea and investigate the development of the phytoplankton bloom, which occurred around the fronts in early March. In addition, we examine the formation of the phytoplankton bloom in the fronts in the light of the critical depth concept.

2. Data and Methods

The Coastal Ocean Process Experiment (COPEX) cruise was carried out between March 1st and 10th, 1997 in the ECS. Geographical map of the ECS is shown with the stations in Fig. 1. CTD casts for vertical profiles of temperature and salinity were conducted using SBE9-11 at 90 stations for the study area. CTD SBE25 was also used for profiles of chlorophyll fluorescence and photosynthetically active radiation (PAR) as well as temperature, salinity, and density at only 21 stations. During the cruise, the surface radiation was obtained by a quantum meter. Chlorophyll-a concentrations were measured at 41 stations using a Turner fluorometer after water samples were filtered by 47 mm GF/F filter and then extracted by 90% acetone.

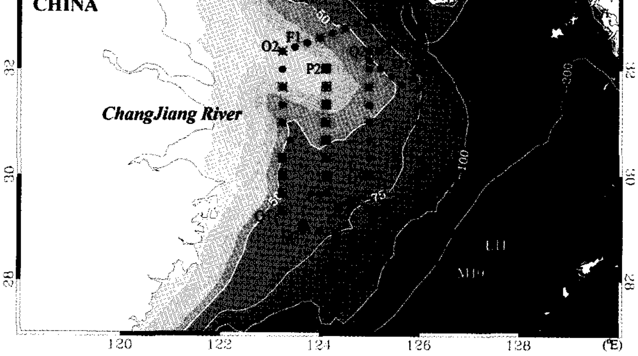


Fig. 1. Map of the Yellow and East China Seas with bathymetry. Symbols indicate observation locations of SBE9-11 (red circles), SBE25 (open squares), and chlorophyll concentrations (stars) in the COPEX cruise in March 1st to 10th, 1997.

Following Sverdrup (1953), the critical depth was calculated as the following equation:

$$\frac{D_{cr}}{1-e^{-K_d D_{cr}}} = \frac{1}{K_d}\frac{I_e}{I_c} \qquad (1)$$

Where D_{cr} is critical depth, K_d is the light attenuation coefficient of sea water, I_e is PAR at the sea surface, and I_c is the irradiance at the compensation depth. I_e was derived from the average value of normalized PAR which was calculated from data measured by the quantum meter during each day. For the energy at the compensation depth (I_c), Sverdrup's (1953) original value is used (1.5 $\mathrm{Wm^{-2}}$ = 0.13 g cal $\mathrm{cm^{-2}\ h^{-1}}$). K_d was calculated with the equation of Kirk (1994), $\frac{ln(E_d(0)) - ln(E_d(z))}{z} = K_d$, where $E_d(0)$ and $E_d(z)$ are the values of downward irradiance just below the surface and at a depth z. In this paper, z is 20 m depth.

NOAA AVHRR image of Sea Surface Temperature (SST) on March 5, 1997 obtained from the satellite receiving center of the Korea Ocean Research & Development Institute was used to compare the surface hydrodynamic patterns with the horizontal distribution of surface chlorophyll-a.

3. Results and Discussion

The satellite SST image of March 5th, 1997 shows that the warm waters of the Tsushima Warm Currents (TWC) flowed into the northern ECS through the passage of Jeju Island (Fig. 2). Thermal fronts were formed between the Kuroshio/TWC and the continental shelf waters. A tongue-shaped pattern extended from the southwestern area of Jeju Island to the shelf area of the northwestern ECS. The location of the fronts in the ECS was similar to the result of Hickox *et al.* (2000).

The horizontal distributions of temperature and salinity at the surface obtained from CTD are shown in Fig. 3. The temperature distribution was similar to the pattern observed from the NOAA SST image shown in Fig. 2.

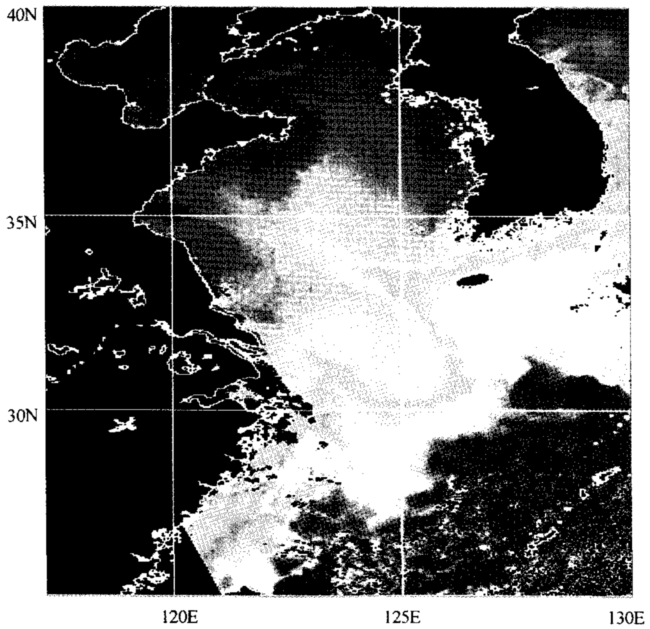


Fig. 2. NOAA AVHRR image of sea surface temperature in the Yellow and East China Seas (May 5th, 1997).

The warm waters flowed into the Yellow Sea through the southwestern area of Jeju Island and into the southeastern area of the Changjiang River Mouth (Fig. 3a). The fronts were clearly distinguishable between the TWC waters and the continental shelf slope waters. The distribution of salinity was similar to that of temperature, but there was another intrusion of low salinity waters in the southeastern Changjiang River Mouth (Fig. 3b). The temperature ranges from 8.5 to 20.8°C and the salinity from 31.67 to 34.68 psu, and steep gradients appear around the fronts. These results confirm the results of previous studies (Zheng and Klemas 1982; Chen *et al.* 1994; Hickox *et al.* 2000).

The spatial pattern of chlorophyll-a in the ECS is shown for the surface and at 20 m depth (Fig. 4). At the surface, high chlorophyll-a concentrations occurred near the fronts in the ECS. The highest chlorophyll-a concentrations were distributed in the southwestern area of Jeju Island (2.9 mg/m^3 in station D10) and the southeastern area of the Changjiang River Mouth (2.8 and 2.0 mg/m^3, respectively for stations Q9 and M6). The pattern recurred at 20 m depth although the concentration was lower. The high chlorophyll-a in the fronts of the ECS in early March was consistent with the results from other studies (Fei 1991; Wu *et al.* 1995; Choi *et al.* 1995) although there were some discrepancies in location and timing.

The vertical structures of temperature, salinity, density, and chlorophyll-a in the transects D and M are shown (Fig. 5 and 6). In D-line, water column was well mixed from D2 to D9 (Fig. 5). Temperature and salinity fronts between the shelf waters and Kuroshio waters appeared

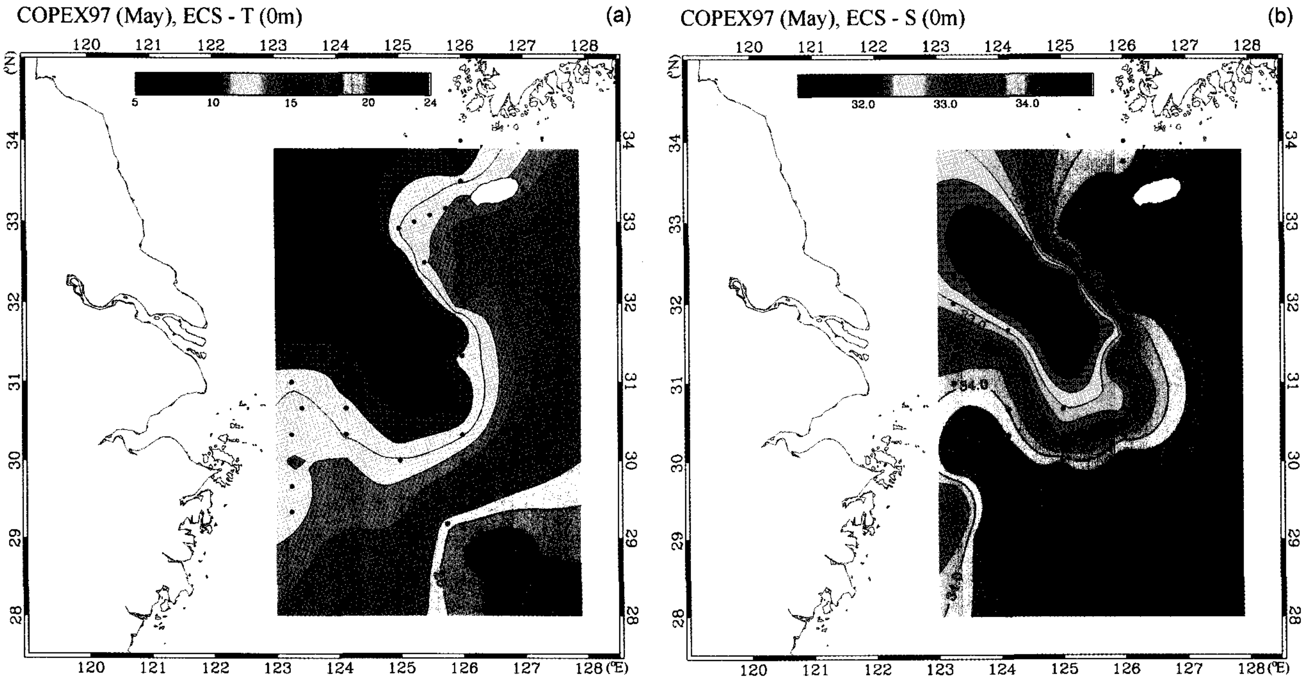
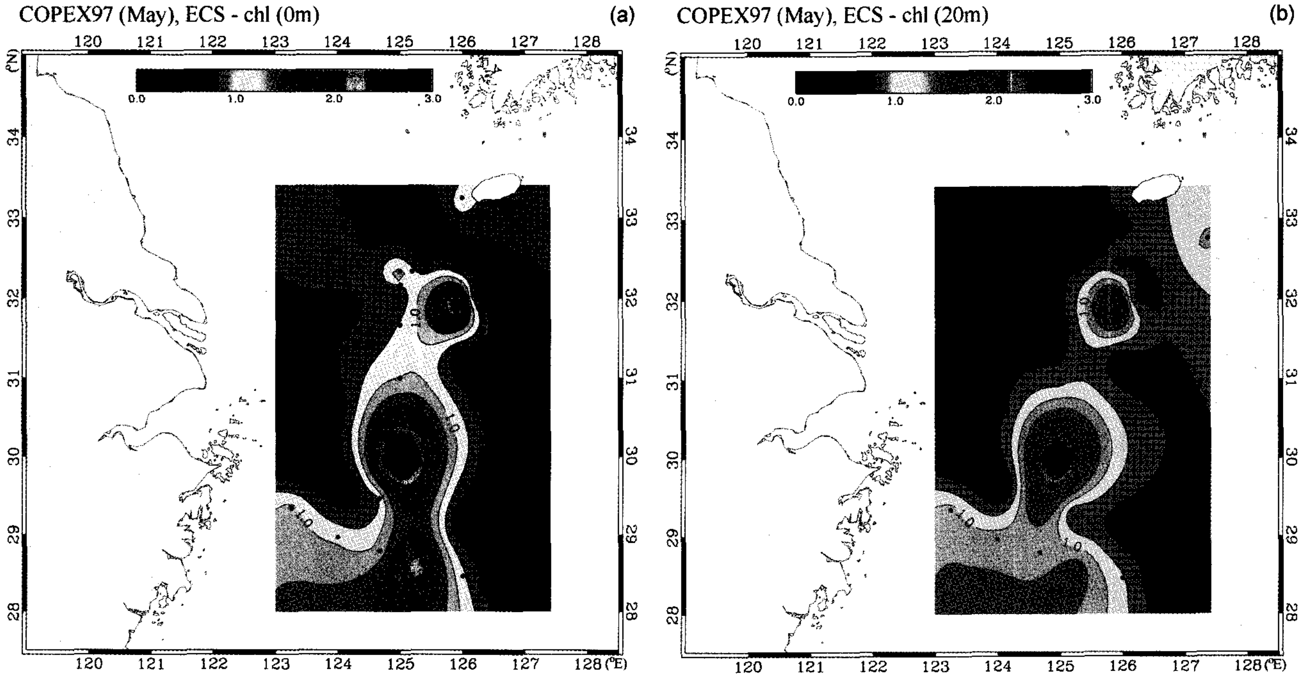


Fig. 3. Contours of (a) sea surface temperature (°C) and (b) salinity (psu) at the surface plotted from data measured using CTD in the COPEX cruise (March 1st to 10th, 1997). Small circles indicate the stations.


COPEX97 (May), ECS - chl (0m) (a)

COPEX97 (May), ECS - chl (20m) (b)

Fig. 4. Contours of chlorophyll concentration ($\mathrm{mg \cdot m^3}$) at (a) the surface and (b) 20 m plotted using the sampling data in the cruise.

around D11 although there were intrusions of colder and diluted waters in the area of ECS waters (between D12 and D13, and between D14 and D16). High chlorophyll-a concentrations appeared near D10 (the highest chlorophyll-a is about 3 mg/m^3 at 10 m), where the water column was stratified close to the fronts. Unfortunately, chlorophyll-a observations were not made at all stations. Especially, there were no chlorophyll-a data in D13 to D16, where two colder and diluted waters appeared on top of the warm and saline waters.

In M-line, steep temperature gradients appeared in between stations M6 and M8 (Fig. 6). Strong vertical stratification existed at M6 to M7 (about 20 to 30 m) while the waters were relatively well mixed from surface down to at least 75 m in between M2 and M5. Water columns in station M6 to M10 were stratified near 40 to 50 m. The patterns in the vertical structures of salinity and density are quite similar to that of temperature, showing that the warm and saline waters flow from the offshore and form the fronts near the station M6. High chlorophyll-a concentration occurred around M6, in which water column was strongly stratified and the fronts appeared. Chlorophyll-a concentration was relatively higher in the ECS waters (shelf side of M6) than in the Kuroshio Warm Current waters (Kuroshio side of M6). The pattern can be explained by the fact that the phytoplankton growth requires nutrients and light in the ocean. Choi *et al.* (1995) has shown that the water transparency measured from Secchi disk increases from the coastal waters to the offshore waters and nutrients are higher near coastal waters and lower in offshore waters, suggesting that high chlorophyll-a concentrations in the tidal fronts result from the supply of nutrients from the coastal waters and bottom waters with good light condition in the northern ECS. It has been reported that the formation of high chlorophyll-a in the fronts between the ECS waters and the Kuroshio waters are due to the bottom topography and oceanic environment such as light and nutrients (Fei 1991). Fei also mentioned that nutrients are supplied from both the river runoff and slope-upwelling in the shelf break. M-line extends from the coastal waters near the Changjiang River to the Kuroshio waters while D-line is more parallel to the coasts. Therefore, it is inferred that the optimal conditions of light and nutrients induced both from the coastal and deep waters enhance the high phytoplankton biomass in the fronts of M-line. The nutricline of nitrate, phosphate and silicates all showed a pattern inclined towards deeper waters supporting this inference (KORDI 1998).

To satisfy both nutrient and light conditions, water column stability is an important factor in phytoplankton

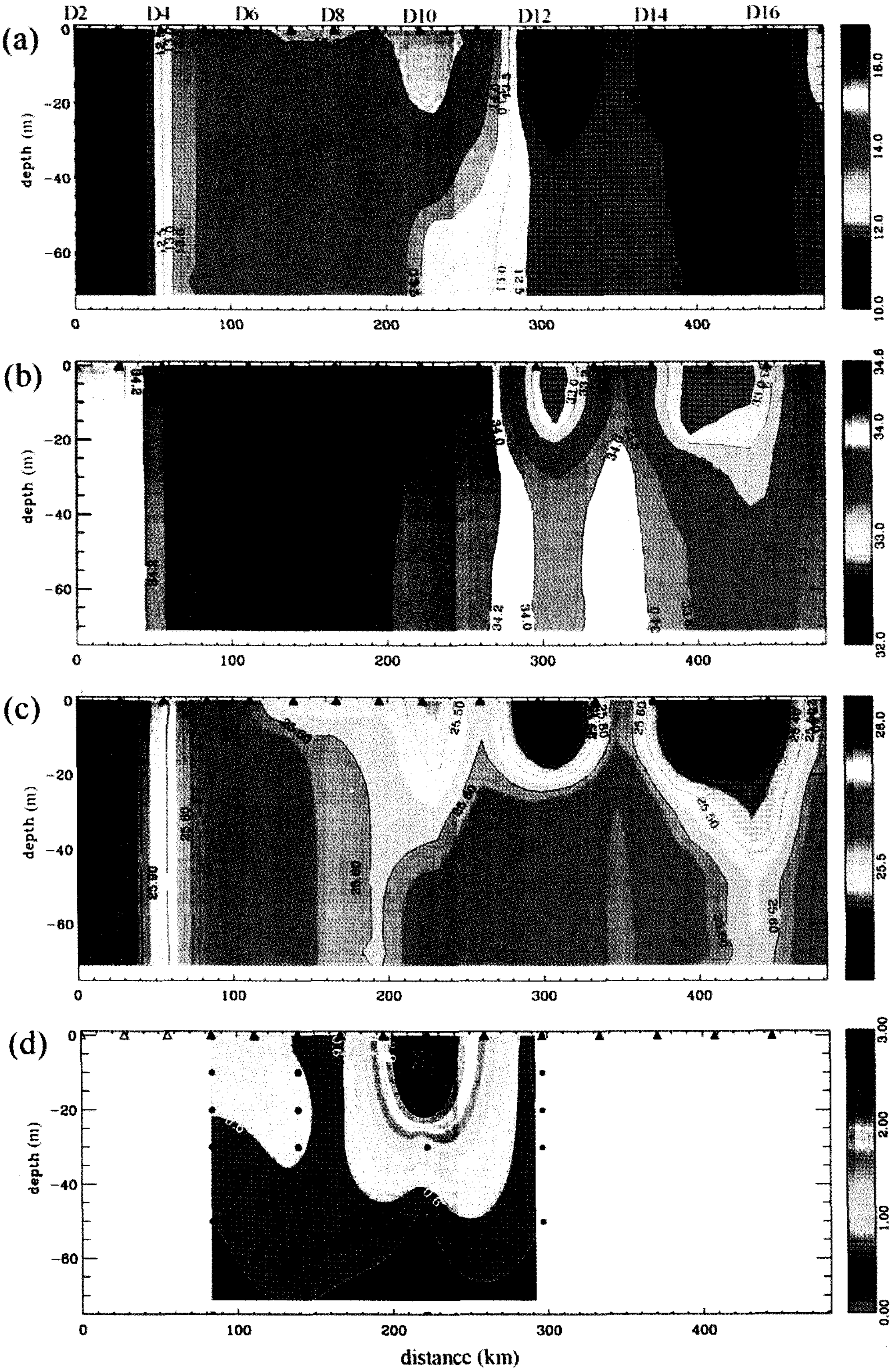


Fig. 5. Vertical sections of (a) temperature (°C), (b) salinity (psu), (c) sigma-t (kg·m^{-3}), and (d) chlorophyll-a (mg·m^{3}) in line D of the COPEX cruise observation during March 1st and 10th, 1997. Transect distance is the distance from the first station, D2. Upper triangles indicate the stations. The contours of temperature, salinity, and sigma-t plotted from CTD measurements in all the stations with 1 m interval from surface to bottom. Data points used for the contour of chlorophyll are shown as black circles.

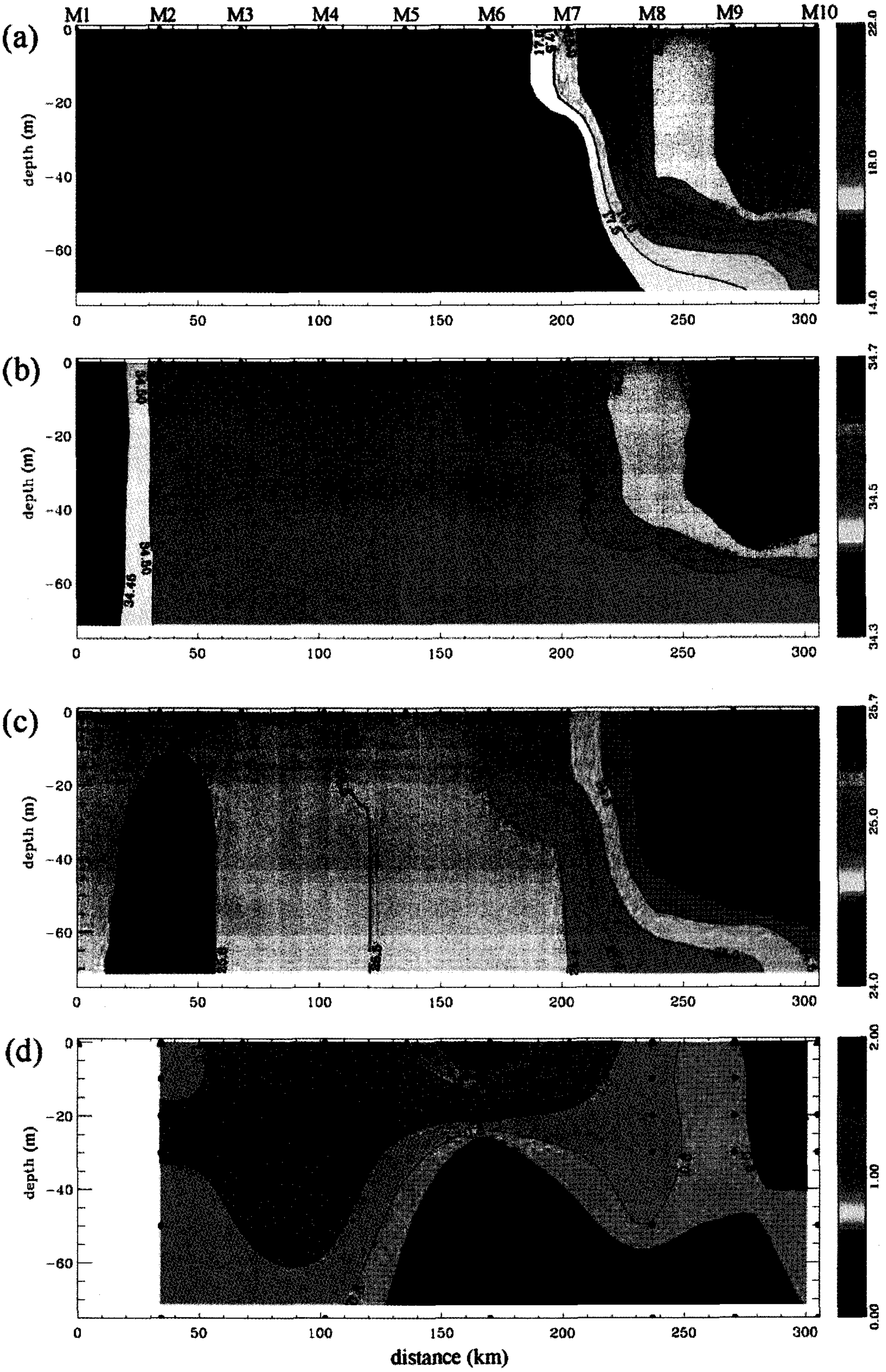


Fig. 6. Vertical sections of (a) temperature (°C), (b) salinity (psu), (c) sigma-t (kg·m^{-3}), and (d) chlorophyll-a (mg·m^{3}) in line M of the COPEX cruise observation during March 1st and 10th, 1997. Transect distance is the distance from the first station, M1.

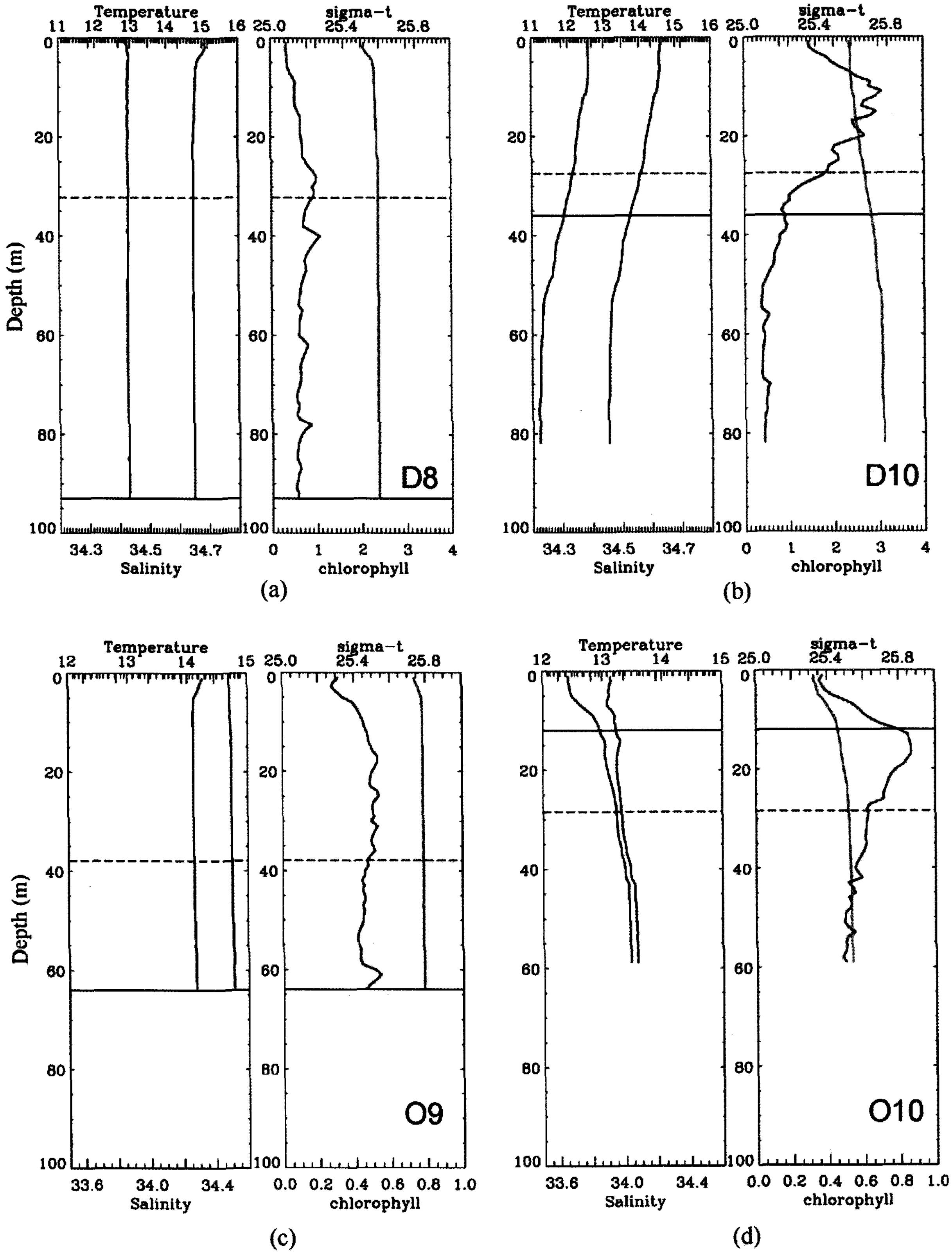


Fig. 7. Profiles of temperature (blue), salinity (red), sigma-t (purple), and chlorophyll-a fluorescence (green) at (a) D8, (b) D10, (c) O9, and (d) O10 (units are °C, psu, kg·m^{-3}, and mg·m^{3}, respectively). Mixed layer depth (calculated as the depth at which sigma-t changes by less than 0.125 kg·m^{-3} from the surface value) and the critical depth are shown as straight lines and dashed lines, respectively.

bloom, especially spring bloom, in the mid-latitude oceans (Sverdrup 1953). In vertically well-mixed waters where nutrients are supplied sufficiently, phytoplankton is mixed out of the euphotic zone before growth can occur. Thus, stratification of water column causes phytoplankton to stay in the euphotic layer. The critical depth was calculated using equation (1) and compared with the vertical profiles of temperature, salinity, density, and chlorophyll fluorescence at four stations (Fig. 7). In stations O9 and D8 (Fig. 7a and c), the water columns were vertically well mixed from surface to the bottom depth. The profiles of the chlorophyll fluorescence were also relatively uniform and the concentrations were low (< 1.0 mg/m^3 at D8 and < 0.5 mg/m^3 at O9). The critical depths were 32.2 m at D8 and 37.9 m at O9, respectively, which were shallower than the mixed layer depths, confirming that light conditions were not satisfactory for the growth of phytoplankton. Profiles of temperature, salinity, and density showed that the waters at the stations D10 and O10 were vertically stratified with mixed layer depths of 36 m and 12 m, respectively (Fig. 6b and d). The chlorophyll-a concentration was higher at D10 than at D8 and at O10 than at O09. In addition, subsurface chlorophyll maximum appeared between 10 and 20 m at both stations, D10 and O10. The chlorophyll concentrations near the subsurface chlorophyll maximum were about 0.9 mg/m^3 at O10 and 3.0 mg/m^3 at D10. The critical depth (28.4 m) was deeper than the mixed layer depth (12 m) at O10, which is consistent with Sverdrup's hypothesis (1953). Although the critical depth (27.5 m) at station D10 was shallower than the mixed layer depth (36 m), the two depths were quite close and the difference might be insignificant considering the uncertainty in exact determination of the critical depth (Smetack and Passow 1990). Thus, it is inferred that the high chlorophyll in the fronts seems to be associated with water column stability as well.

Understanding development of phytoplankton bloom has important implications for higher trophic levels. Fei (1991) has shown that the high phytoplankton biomass in the frontal area has a close relationship with fishing grounds in the ECS.

One thing to notice is that construction of the Three Gorges Dam, which is the largest one in the world, has been continued on the Changjiang River since 1992 and was recently completed in May, 2006. The dam will be operating in 2009. It has been shown that sediment discharge in the Changjiang River decreased more than 20% from the 1980s to 1990s while water discharge increased 10% as a result of human activities such as deforestation and impoundments (Yang *et al.* 2002). Our results are based on the data measured about one decade ago. So the phytoplankton bloom in the fronts of the ECS could be strongly influenced by changes in the discharge of fresher waters and suspended sediments from the Changjiang River since the construction of the Three Gorges Dam. Therefore, it would be interesting to see whether there is any change in formation of the fronts and development of spring phytoplankton bloom in the area. For better understanding of the development of spring blooms in the frontal areas of the ECS as well as long-term changes due to the human activities such as the Three Gorges Dam, further investigation is required.

Acknowledgments

Authors appreciate Drs. SangHeon Lee, Stephanie Henson and anonymous reviewers for valuable comments in previous manuscript. Mr. Jisoo Park contributed to collecting *in situ* measurements in the cruise and Ms. Suk Yoon helped to process AVHRR SST image.

References

Agusti, S. and C. Duarte. 1999. Phytoplankton chlorophyll a distribution and water column stability in the central Atlantic Ocean. *Oceanologia Acta*, **22**(2), 193-203.

Beardsley, R.C., R. Limeburner, H. Yu, and G.A. Cannon. 1985. Discharge of the Changjiang (Yangtze) in to the East China Sea. *Cont. Shelf. Res.*, **4**, 57-76.

Chen, C., R. Beardsley, and R. Limeburner. 1994. Comparison of winter and summer hydrographic observations in the Yellow and East China Seas and adjacent Kuroshio during 1986. *Cont. Shelf Res.*, **14**, 909-929.

Choi, J.-K., J.-H. Noh, K.-S. Shin, and K.-H. Hong. 1995. The early autumn distribution of chlorophyll-a and primary productivity in the Yellow Sea, 1992. *The Yellow Sea*, **1**, 68-80.

Fei, Z. 1991. An analysis on the formation mechanism of the distribution of high content of chlorophyll-a in the continental shelf edge waters of East China Sea. *Acta Oceanologica Sinica*, **11**(1), 97-107.

Fournier, R.O., M. Van Det, N.B. Hargreaves, J.S. Wilson, T.A. Clair, and R. Ernst. 1984. Physical factors controlling summer distribution of chlorophyll a off southwestern Nova Scotia. *Limnol. Oceanogr.*, **29**(3), 517-526.

Hickox, R., I. Belkin, P. Conillon, and Z. Shan. 2000. Climatology and seasonal variability of ocean fronts in the East China, Yellow and Bohai Seas from satellite SST data. *Geophys. Res. Lett.*, **27**(18), 2945-2948.

Jones, K. J. and R. J. Gowen. 1990. Influence of stratification and irradiance regime on summer phytoplankton composition in coastal water and shelf of the British Isles. *Estuar. Coast Shelf. Sci.*, **30**, 557-567.

Kirk, J.T.O. 1994. Light and photosynthesis in aquatic ecosystems, 2nd. Cambridge University Press. p. 119-120.

KORDI, 1998. Ocean Circulation in the Western and Middle Part of East China Sea. KORDI, BSPE97603-00-1042-1. 278 p.

Molion, M. 1998. Photoadaptive response during the development of a coastal Antarctic diatom bloom and relationship to water column stability. *Limnol. Oceanogr.*, **43**(1), 146-153.

Pingree, R.D., P.M. Holligan, G.T. Mardell, and R.N. Head. 1976. The influence of physical stability on, spring summer and autumn phytoplankton blooms in the Celtic Sea. *J. Mar. Biol. Assoc. U.K.*, **56**, 845-874.

Smetacek, V. and U. Passow, 1990. Spring bloom initiation and Sverdrup's critical-depth model. *Limnol. Oceanogr.*, **35**, 228-234.

Sverdrup, H.U. 1953. On conditions for the vernal blooming of phytoplankton, *J. Cons. Int. Explor. Mer.*, **18**, 287-295.

Takeoka, H., S. Matsuda, and T. Yamamoto. 1993. Processes causing the chlorophyll a maximum in the tidal front in Iyo-Nada, Japan. *J. Oceanogr.*, **49**, 57-70.

Wu, Y.-L., Y.-J. Guo, and Y.-S. Zhang. 1995. Distributional characteristics of chlorophyll-a and primary productivity in the Yellow Sea. *The Yellow Sea*, **1**, 81092.

Yang, S., Q. Zhao, and I.M. Belkin. 2002. Temporal variation in the sediment load of the Yangtze river and the influences of human activities. *J. Hydrology*, **26**, 56-71.

Zeng, Q. and V. Klemas. 1982. Determination of winter temperature patterns, fronts, and surface currents in the Yellow Sea and East China Sea from satellite imagery. *Remote Sens. Environ.*, **12**, 201-218.