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Effect of the Kuroshio intrusion on the chlorophyll distribution in the southern East China Sea during spring 1993

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Abstract—In order to assess the effect of the Kuroshio intrusion on phytoplankton biomass in the southern East China Sea north of Taiwan, chlorophyll *a* distributions observed before and after the recession of the seasonal Kuroshio intrusion were compared. Weekly hydrographic surveys and moored current meter data showed that the Kuroshio intruded onto the shelf under the prevailing northeasterly in early April 1993, and it retreated in early May 1993 shortly after the cessation of the northeasterly. The chlorophyll *a* distribution showed an eminent increase with a concentric distribution pattern, which was obviously related to the re-emergence of the year-round upwelling at the shelf break northeast of Taiwan. Strengthened upwelling was evidenced by a concomitant increase of nitrate concentration in the subsurface water near the shelf break. The mean value of the euphotic zone integrated chlorophyll *a* concentration in the normal upwelling area increased from 16 to 36 mg m^{-2} after the Kuroshio withdrawal. The high chlorophyll *a* concentration in the upwelling region was shown associated with the high primary productivity measured in the following year, May 1994. The euphotic zone integrated chlorophyll *a* concentration and primary production in the upwelling water were found to be 33 mg m^{-2} and 1540 mgC m^{-2} d^{-1}, respectively. The higher chlorophyll and primary production was apparently the results of ample nutrient supply from the upwelling. At the same time, very high primary production was found in the mainland China coastal water with a value of 1900 mgC m^{-2} d^{-1} corresponding to a dinoflagellate bloom with population densities exceeding 1×10^4 cells l^{-1}. The Kuroshio water, on the other hand, has the lowest primary production value of 420 mgC m^{-2} d^{-1}. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Upwelling systems have always been an attractive site for oceanographic studies due to their eminent biological, physical and chemical signals. In the southern East China Sea northeast of Taiwan, the impingement of the Kuroshio onto the continental shelf induces upwelling in association with a subsurface countercurrent landward of the impinging

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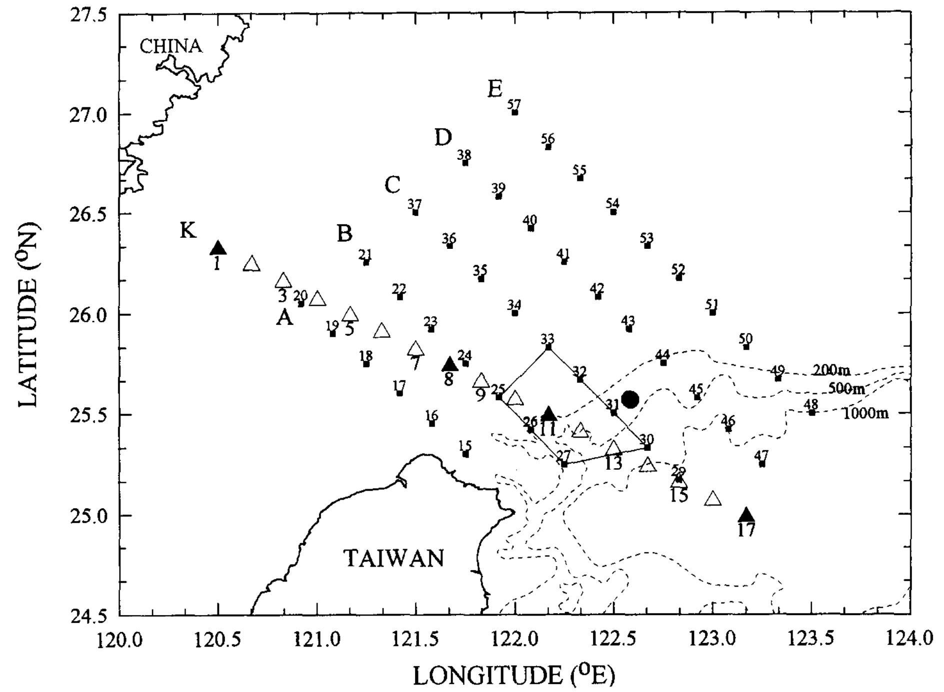


Fig. 1. Map of the southern East China Sea showing sampling stations. Mooring station (●); transect K stations (△); primary productivity stations (▲). See also Table 1 for cruises information. The upwelling area is within the stations connected by solid lines.

current (Chuang *et al.*, 1993). A dome-shaped pool of upwelled Kuroshio subsurface water (UKSW) has been shown present at the shelf break northeast of Taiwan all year round (Gong, 1992; Liu *et al.*, 1992a; Gong *et al.*, 1995a). The outcropping of the UKSW often results in a cold patch which can be found most of the time in an area bounded by stations 25, 26, 27, 30, 31, 32 and 33 in Fig. 1 (Gong *et al.*, 1992; Lin *et al.*, 1992). High chlorophyll concentrations have been observed around this region (Chen, 1992; Gong *et al.*, 1993, 1995b).

The outcropping of the UKSW is sometimes suppressed by outflowing of shelf water under persistent southwest monsoon (Gong *et al.*, 1992). In the present study, evidence shows that the upwelling can be suppressed or displaced by the shelfward intrusion of the Kuroshio surface waters (KSW) which intrudes onto the shelf slope in mid-October and retreats off the shelf in May (Sun, 1987; Lin *et al.*, 1992; Tang and Yang, 1993; Chuang and Liang, 1994). The mechanism of intrusion is not well understood but has been linked to several plausible processes, such as Ekman drift of the KSW, cooling of shelf water, suppression of the Kuroshio branch current in the Taiwan Strait and reduced stratification, all under the influence of the northeast monsoon (Chao, 1991; Chern and Wang, 1992; Liu *et al.*, 1992b; Chern and Wang, 1994; Chuang and Liang, 1994). When the northeast monsoon subsides, the Kuroshio quickly recedes from the shelf probably due to the resumption of the Kuroshio branch current through the Taiwan Strait (Wang and Chern, 1988, 1989; Chao, 1991).

A water mass that usually occupies the inner shelf northwest of Taiwan during the northeast monsoon period is the low-salinity and nutrient-laden mainland China coastal water (CCW; Gong, 1992; Liu *et al.*, 1992b; Gong *et al.*, 1995a). The interaction among these water masses inevitably will alter the availability of nutrients, influence the rate of carbon fixation, and finally determine the phytoplankton biomass distribution.

The primary productivity of the southern East China Sea has been investigated by a few snapshot studies (Hung *et al.*, 1980; Fei *et al.*, 1987), and a general pattern of chlorophyll distribution has been reviewed by Guo (1991). However, they provided little insight into the relationships among physical forcing, hydrography and the variability of primary productivity and chlorophyll concentrations in this area. The major purpose of this paper is to show, from a series of spring cruises in 1993, how nutrient (nitrate) and chlorophyll distribution patterns in the southern East China Sea north of Taiwan changed in response to the cessation of the shelfward intrusion of the KSW. Primary productivity in the three water masses of the southern East China Sea north of Taiwan was also measured at the same time in 1994 to gain more insight about the relationship between nitrate and chlorophyll distribution.

MATERIALS AND METHODS

Study area and sampling

The study was performed in the southern East China Sea north of Taiwan (Fig. 1) as part of the multidisciplinary KEEP (Kuroshio Edge Exchange Processes) program. Four weekly cruises (cruises 352A–D) were conducted on board the R/V *Ocean Researcher I* during 14 April to 15 May 1993 to investigate the biogeochemical responses to the change of shelf conditions during the change of the prevailing wind. Transects B–E and A–E were occupied on the first and the third cruises, respectively, and transect K was occupied on the second and the fourth cruises (Fig. 1). The first and the third cruises were used to examine the effect of the Kuroshio intrusion on the phytoplankton distribution, because their areal coverages were more suitable to study the change in distribution pattern. An additional cruise (cruise 386) was conducted along transect K in May 1994 to investigate the primary productivity in different nutrient regimes. Table 1 lists the detailed information about the cruises. Water samples were collected from a SeaBird CTD-General Oceanic Rosette assembly with 2.5-liter Teflon-coated Go-Flo bottles. Irradiance was measured with a 2π quantum scalar irradiance meter (L185B; Licor Inc.) on cruise 386. The depth of the euphotic zone was defined as the level of 1% of the surface light. The depths of the euphotic zone for the earlier cruises 352A and 352C were calculated from the pigment (chlorophyll *a* + phaeopigment) profile by using the relationship between the euphotic

Table 1. *Cruise information* (*see also Fig.* 1 *for the location of transect*)

Cruise no.	Date	Transect	No. of station
352A	04.14–04.19 1993	B, C, D, E	36
352B	04.21–04.29 1993	K	17
352C	05.01–05.05 1993	A, B, C, D, E	42
352D	05.07–05.15 1993	K	17
386	05.04–05.10 1994	K	17

depth and the mean pigment concentration described in Morel (1988). The relationship was shown applicable in our study area based on the recent results (Gong and Liu, 1995).

Mooring observations

A mooring with current meter (Aanderaa RCM-7) anchored at the depth of 110 m was deployed on the slope northeast of Taiwan (Fig. 1) from 28 March to 2 August 1993. The sampling interval was set at 30 min. The water depth of the shelf break is about 120 m (see Fig. 2), so the meter can effectively measure the cross-slope current.

Nutrients, chlorophyll a *and phytoplankton composition*

Water samples for nutrients analyses were subsampled with clean 100-ml polypropylene bottles and were frozen immediately with liquid nitrogen. Nitrate was analyzed with a self-designed flow injection analyzer and was reduced to nitrite with a cadmium wire, which was activated with a copper sulfate solution (Gong, 1992). Chlorophyll *a* concentrations (Chl*a*; mg m^{-3}) were obtained from the calibrated in-situ fluorescence of the Sea Tech fluorometer mounted on the CTD. The relationship between in-situ fluorescence and measured acetone extracted Chl*a* in seawater of the study area had been reported by Gong *et al.* (1993, 1995b). They showed that the relationship between in-situ fluorescence and measured acetone-extracted Chl*a* was very stable both temporally and spatially. Therefore, it is reasonable to use the calibrated in-situ fluorescence to present Chl*a* in the present study. Euphotic zone integrated Chl*a* concentrations were calculated by trapezoidal integration. The samples for phytoplankton species determination were preserved with acidic Lugol's solution (Throndsen, 1978) and examined using a Nikon microscope (Optiphot-2) at 100×.

Primary productivity

Primary productivity (PP) experiments on cruise 386 were conducted by the ^{14}C assimilation method (Parsons *et al.*, 1984; Shiah *et al.*, 1995). Two light and one dark 250-ml clean polycarbonate bottles (Nalgene) were filled with water which was pre-screened through 200-μm woven mesh (Spectrum) to remove large organisms and particles and inoculated with 10 μCi $NaH^{14}CO_3$. Incubation bottles were all pre-washed by soaking in a 10% HCl solution overnight and rinsing at least three times with Milli-Q water and also rinsed with sample waters three times before use. One clear bottle was immediately filtered as the time zero control. PP samples were incubated on deck from dawn to down and cooled with running seawater. Duplicate light bottles for a given depth were covered with different layers of nylon stockings to simulate the degree of the light penetration at that particular depth. The correlation between layers of nylon stockings (N) and I_z/I_0 (the ratio between light intensity at depth z and that at sea surface) previously determined at the laboratory was $N = -3.93 \times \ln(I_z/I_0)$, $n = 10$, $R^2 = 0.99$.

Following retrieval, the bottles were stored in the dark and processed immediately. From each light bottle, 0.25-ml was taken and transferred to a 15-ml scintillation vial containing 2.5 ml of Milli-Q water and 0.25 ml of ethanolamine, and then 10 ml of scintillation cocktail (Ultima Gold) was added. This was to determine the total activity of $H^{14}CO_3$ in the sample. The water samples were then filtered through 25-mm GF/F filters.

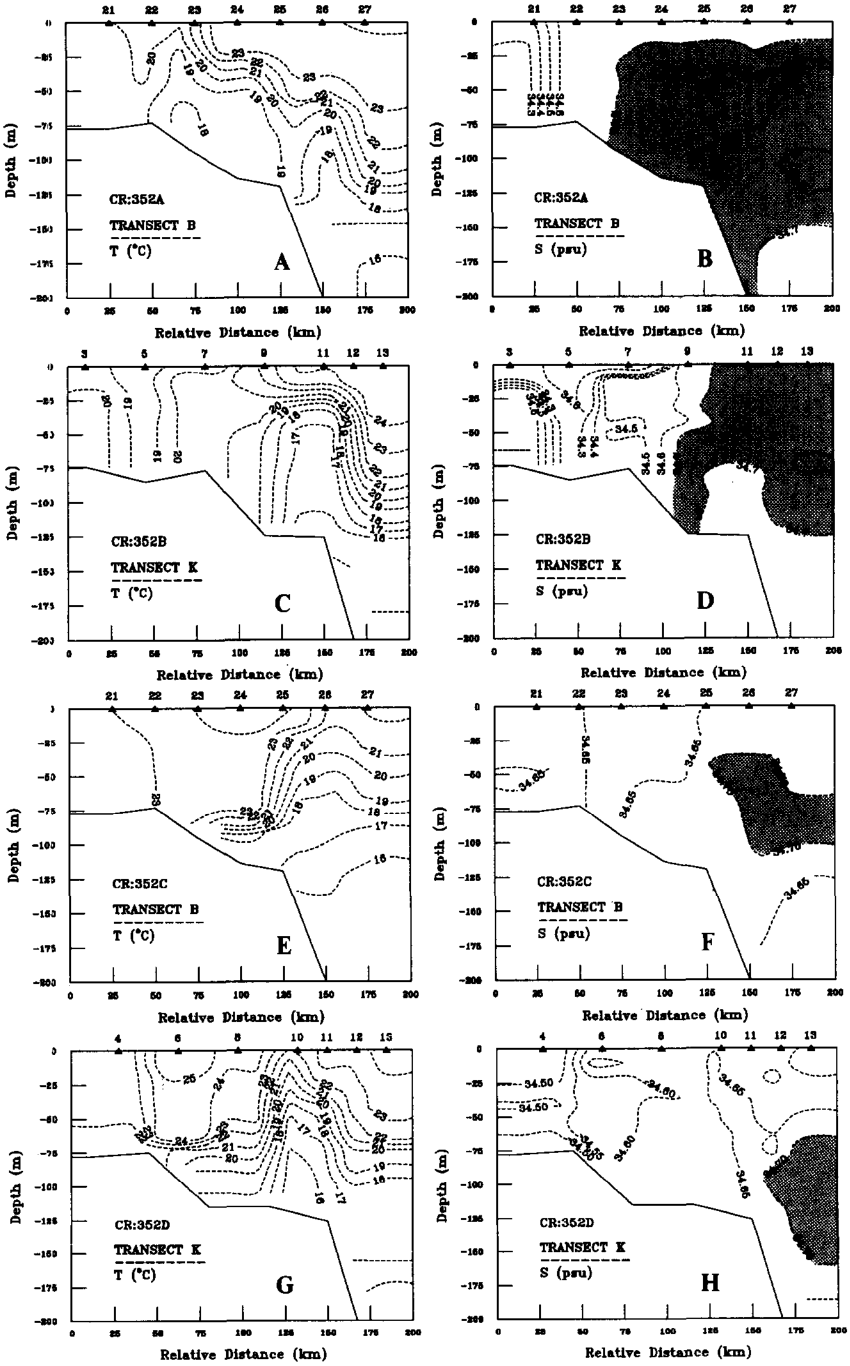


Fig. 2. Sections of temperature and salinity during cruises 352A–D. See also Table 1 and Fig. 1.

Pumping pressure was maintained below 100 mmHg to prevent the possible damage of cells. The filters then were placed in scintillation vials and stored in the dark. After being returned to the laboratory, 0.5 ml of 0.5 M HCl was added to the vials containing filters, which were left open under the hood at room temperature overnight. The time zero sample, total activity and incubated samples were counted in a liquid scintillation counter (PACKARD 1600) after the addition of 10 ml scintillation cocktail to the vials.

RESULTS

The weekly hydrographic surveys in the spring of 1993 in the study area provided a good opportunity to study the Kuroshio interaction with the East China Sea shelf during a transition period of the KSW intrusion. The sections of temperature and salinity along transects B and K from the four consecutive weekly cruises clearly depict the withdrawal of the KSW from the shelf to the slope (Fig. 2).

Shelfward intrusion of the KSW northeast of Taiwan was observed on the first cruise in mid-April 1993. The salty KSW (>34.7 psu) occupied most of the upper water column on the outer shelf and slope (Fig. 2B). This water formed a rather thick surface mixed layer of 20–50 m with a temperature around 23°C (Fig. 2A). On the following cruise, the high-salinity water (indicated by the stippled area in Figs 2D, 2F and 2H) withdrew gradually from the shelf to the slope. While the KSW retreated, the UKSW started to dome up at the shelf break, which signaled upwelling. Even at the peak of KSW intrusion, the upwelling water still existed at greater depth (Fig. 2A). However, while the upward movement of cold water was suppressed by the KSW, the upwelling was not detectable at the sea surface (Figs 2A and 3A). Part of the upwelled water might be pushed onto the shelf and formed a pool of cold salty water near the bottom between stations 22 and 23 (Fig. 2A). On the third cruise (352C), a well-developed upwelling dome existed near the shelf break between stations 26 and 27, with cool water (22°C) outcropping at the surface (Fig. 2E).

The horizontal distributions of various water types before and after the recession of the KSW are illustrated by the sea surface temperature and salinity contours observed on the first (352A) and the third (352C) cruises (Fig. 3). On the first cruise, the KSW with higher temperature (23°C isotherm) and salinity (>34.7 psu) occupied the entire study area from the mid-shelf to the slope north of Taiwan (Figs 3A and 3B), indicating the extent of the Kuroshio intrusion. On the third cruise, a pool of cold water bounded by the 22°C isotherms existed around the shelf break north of Taiwan (Fig. 3C), indicating that the intruding KSW gave way to the upwelled UKSW. However, a band of high-salinity water (>35.7 psu) still occupied the outer shelf east of the upwelling region (Fig. 3D), suggesting that the KSW did not retreat entirely from the shelf but its main axis had shifted eastward.

A cold-water front on the inner shelf near stations 37 and 38 was observed on both cruises (Figs 3A and 3C). The salinity of this cold water was significantly lower than that of the UKSW (Figs 3B and 3D), suggesting it contained significant portion of the CCW which dispersed from the northwest.

The current meter data support the view that the observed temperature and salinity distribution was caused by a change in the Kuroshio flow pattern (Fig. 4). The Kuroshio intrusion started in mid-October 1992, a month after the onset of the northeast monsoon. Chuang and Liang (1994) showed that the cross-slope current did not remain constant but fluctuated under wind modulation in accordance with the synoptic weather pattern. During late March to mid-April 1993, an on-shelf current with a maximal speed of 50 cm

s^{-1} at the depth of 110 m was observed under the prevailing northeast monsoon (Fig. 4). In mid-April (during cruise 352A), the wind slackened and started to fluctuate in its direction. Ten days later (during cruise 352B), the cross-slope current reversed abruptly and marked the end of the KSW intrusion. The sudden current-reversal could have been caused by the out-flow of Taiwan Strait water associated with the resumption of the Kuroshio branch current (Wang and Chern, 1988, 1989; Chao, 1991). Subsequently, the current weakened and fluctuated with the mean velocity of less than 15 cm s^{-1}.

The spatial distribution of nitrate concentrations at 50 m depth of cruises 352A and 352C were totally different (Figs 5A and 5B). All the isopleths observed on cruise 352C located more southeastward than those of cruise 352A. The concentric nitrate isopleths found on cruise 352C clearly marked the position of the upwelling (Fig. 5B). The corresponding distributions of euphotic zone integrated Chl*a* (ICHLA) ranged from 13 to 39 and 12 to 55 mg m^{-2} for cruises 352A and 352C, respectively (Figs 5C and 5D). A well-defined ICHLA core was centred around the upwelling region on cruise 352C with maximum higher than 50 mg m^{-2}. On the other hand, during the intrusion of KSW (cruise 352A), ICHLA values were low ($\leq$20 mg m^{-2}) in the normal region of UKSW outcropping. Instead, a rather high ICHLA ($\sim$39 mg m^{-2}) was observed at station 23, which was far apart from the region of ICHLA maximum (station 32) observed on cruise 352C. Distribution of surface Chl*a* (not shown) was similar to ICHLA distribution, and the concentrations ranged from 0.1 to 1.4 and 0.1 to 1.7 mg m^{-3} for cruises 352A and 352C, respectively.

The influence of upwelled nitrate on phytoplankton biomass and productivity were investigated during cruise 386 in May 1994. Stations 1, 8, 11 and 17 can be readily assigned to three water masses according to their *T–S* characteristics (Fig. 6A). The low salinity of station 1 represented the CCW; the high salinity of station 17 represented the KSW; and the intermediate salinity with relatively low temperature of stations 8 and 11 represented the upwelled UKSW (Chern and Wang, 1989; Liu *et al.*, 1992b; Gong *et al.*, 1995a). The depth of euphotic zone increased seaward from 20 m (station 1) to 55 m (station 17). Temperature ranged from 19°C (station 1) to 27°C (station 17) and did not change much within the euphotic zone of each station. Nitrate concentrations in the bottom of the euphotic zone ranged from undetectable (<0.1 μM) to 2.5 μM (Fig. 6B).

Surface Chl*a* ranged from 0.2 mg m^{-3} at station 17 to 2.8 mg m^{-3} at station 1 (Fig. 6C). ICHLA for stations 1, 8, 11 and 17 were 46, 10, 33 and 16 mg m^{-2}, respectively. The high Chl*a* level at station 1 was caused by a bloom of athecate dinoflagellates with population densities exceeding 1×10^4 cells l^{-1}. PP profiles at these four stations all decreased exponentially with depth although the absolute values varied from station to station (Fig. 6D). The highest and lowest surface PP was observed at stations 1 and 17 with values of 134 and 11 mgC m^{-3} d^{-1}, respectively. Surface PP of the upwelling stations (i.e. stations 8 and 11) showed intermediate values ranging from 30 to 93 mgC m^{-3} d^{-1}. The integrated primary production for the euphotic zone at stations 1, 8, 11 and 17 was 1900, 430, 1540 and 420 mgC m^{-2} d^{-1}, respectively.

DISCUSSION

The results indicate that, during the Kuroshio intrusion in early April 1993, the interaction between the intruding KSW and the upwelling UKSW caused changes in concentration of nitrate in the study area, which in turn changed the euphotic zone integrated Chl*a* level. At the shelf break, the intruding KSW masked the upwelling region

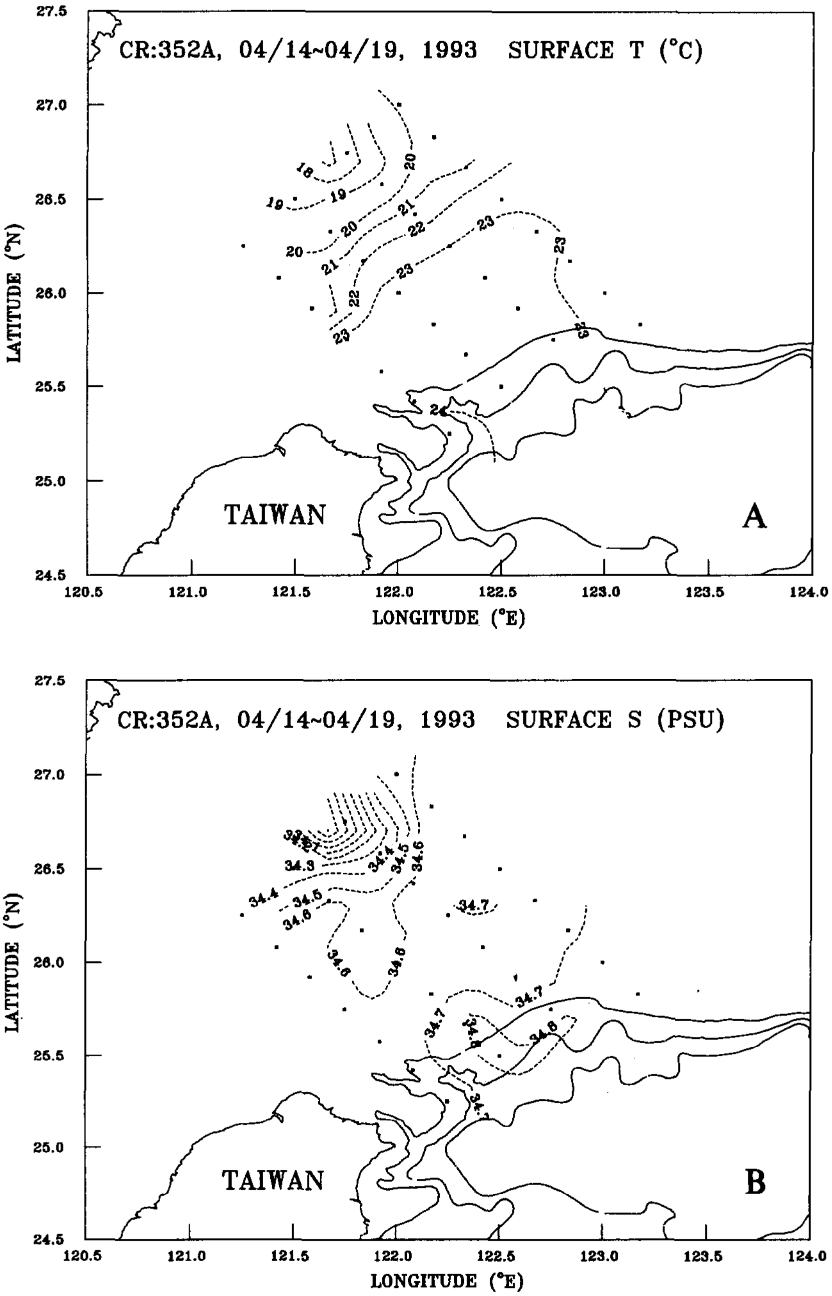
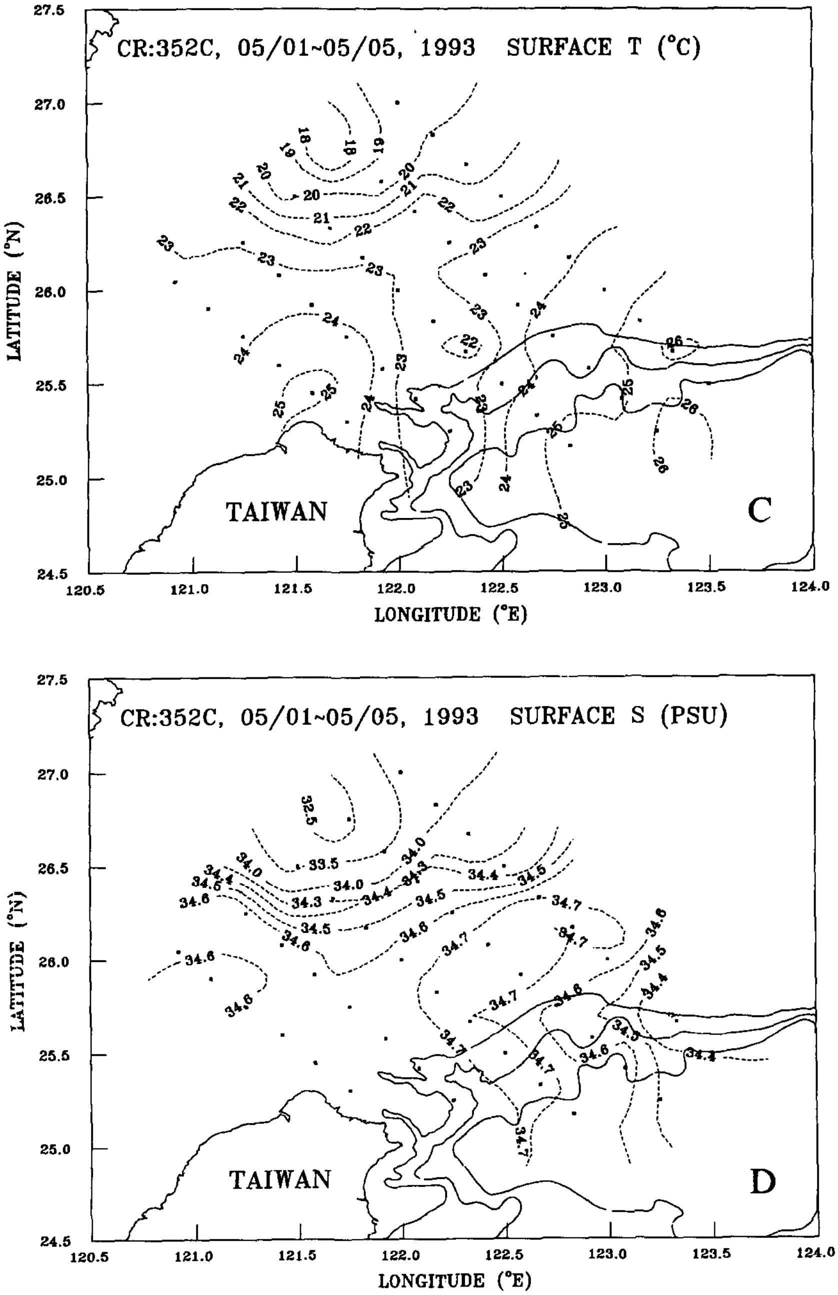


Fig. 3. Sea surface temperature and salinity (dotted) during cruises 352A and 352C.



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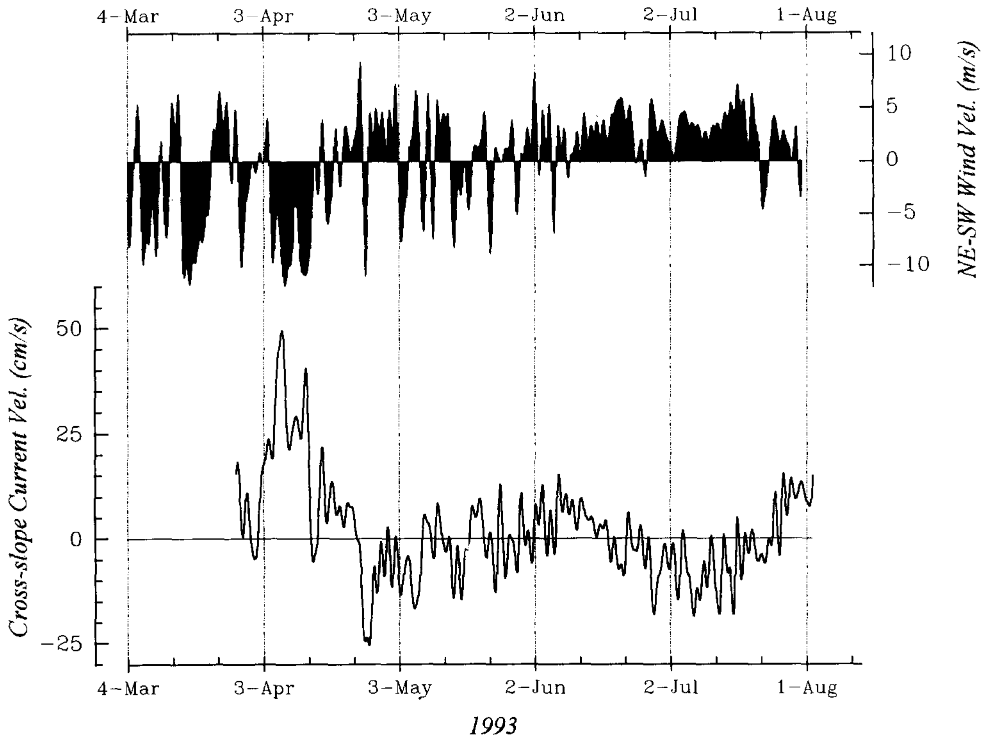

Fig. 4. Time series of wind speed and the cross-slope current velocity recorded at the depth of 110 m on the shelf edge.

with low-chlorophyll, nutrient-poor, and low-density water (Figs 2A, 3A, 5A and 5C). The pool of UKSW in the subsurface layer over the outer shelf was pushed toward northwest and pressed against CCW indicated by the low temperature and low salinity around stations 37 and 38 (Figs 3A and 3B). As a result, the subsurface (50 m) high nitrate water was split into two patches (Fig. 5A), which supported the development of two chlorophyll-rich centers in the overlying water (Fig. 5C). The two-patch pattern did not appear in the distribution of the sea surface temperature (Fig. 3A), because the warmer KSW overlaid the denser UKSW. In fact, KSW penetrated to the mid-shelf during intrusion and formed a strong temperature gradient against the CCW in the surface layer (Fig. 3A).

Starting from 23 April, the KSW intrusion started to recede (Fig. 4). Subsequently, the UKSW outcropped at the shelf break forming the characteristic patch of nutrient-enriched cold water as observed during cruise 352C (Figs 2E and 3A). High level of ICHLA was also formed around the normal upwelling region (Fig. 5D).

Nitrate concentration in the subsurface water is commonly used as an indicator of the availability of new nutrients to phytoplankton in the euphotic zone (Dugdale and Goering, 1967). In the southern East China Sea, regions with high level of nitrate at 50 m depth coincided well with regions of high ICHLA (Fig 5). This implies that new nitrogen is likely to be a major controlling factor of phytoplankton biomass and PP in this region. Additional proof came from the PP measurement during the 1994 spring cruise (cruise 386). The *T–S* diagram indicated that waters at stations 8 and 11 both belonged to the UKSW (Fig. 6A). However, station 11 was closer to the upwelling center, as judged by the nitrate profiles (Fig. 6B). The higher Chl*a* level and PP at station 11 was likely a result of ample nutrient supply from the upwelling (Figs 6C and 6D). A similar conclusion was drawn by Wilkerson and Dugdale (1987) for the California upwelling system.

Since the low-salinity CCW is also rich in nutrients, high ICHLA observed at stations along the north and northwest edges of the study area could be a result of CCW influence (Figs 5C and 5D). The contribution of the CCW to the phytoplankton growth in the study area was not as significant as that of the UKSW as observed on the cruises in 1993, because high Chl*a* concentrations were always associated with high-salinity waters (~34.6 psu) at NW stations whereas the Chl*a* level in the less salty CCW was lower. Other evidence comes from the 50-m nitrate concentrations data shown in Figs 5A and 5B. The area with nitrate concentrations $>5.0\,\mu\text{M}$ was occupied by the UKSW rather than CCW as indicated by the salinity (~34.6 psu; Figs 3B and 5A). However, on cruise 386 in 1994, CCW indeed contained high level of Chl*a*, but that was at a station (station 1 on transect K) very close to the coast of China (Fig. 6). The surface water had a significant nitrate concentration (~1 μM), which could have induced the intensive phytoplankton growth.

The impact of the Kuroshio intrusion on the continental shelf ecosystem can be evaluated from different angles. The upwelling has been proven as a permanent feature on the edge of the southern East China Sea north of Taiwan. With phytoplankton biomass and PP much higher than surrounding waters, the upwelling center could have been an important source of particulate organic carbon (POC) feeding the seaward flux of carbon in association with the cyclonic eddy or filament northeast of Taiwan (Chern *et al.*, 1990; Liu *et al.*, 1995; Ma, 1995). Its importance in cross-shelf carbon flux is currently under intensive study (Liu, 1994). By suppressing nutrient supply from the UKSW to this area, the intrusion of KSW apparently reduces phytoplankton growth at the shelf break area northeast of Taiwan. The time-integrated primary production and the associated POC export in the study area in winter might be reduced, since such intrusion must have been prevalent during the northeastern monsoon season (Lin *et al.*, 1992; Gong, 1992; Hsueh *et al.*, 1992; Chuang and Liang, 1994). On the other hand, the Kuroshio intrusion brought nutrient-enriched UKSW to the mid-shelf, where the water is usually nutrient-depleted (Gong *et al.*, 1996), and increased the PP there. Consequently, the ecosystem in the mid-shelf may have benefited from the enhanced productivity caused by the intrusion.

CONCLUSION

Spatial and temporal variability of surface and euphotic zone integrated Chl*a* concentrations and the subsurface (50 m) nitrate concentrations observed during four weekly cruises in Spring 1993 in the southern East China Sea north of Taiwan could be largely explained by the successions of different water masses. These included the Kuroshio surface water, the upwelled Kuroshio subsurface water, and the mainland China coastal water. The intrusion of the Kuroshio surface water suppressed the supply rate of subsurface nitrate to the euphotic zone, and thereby reduced Chl*a* concentrations within the normal upwelling area. Outside the upwelling area, especially in the northwest of the study area, the Chl*a* rich areas were likely to be supported by the nitrate-enriched

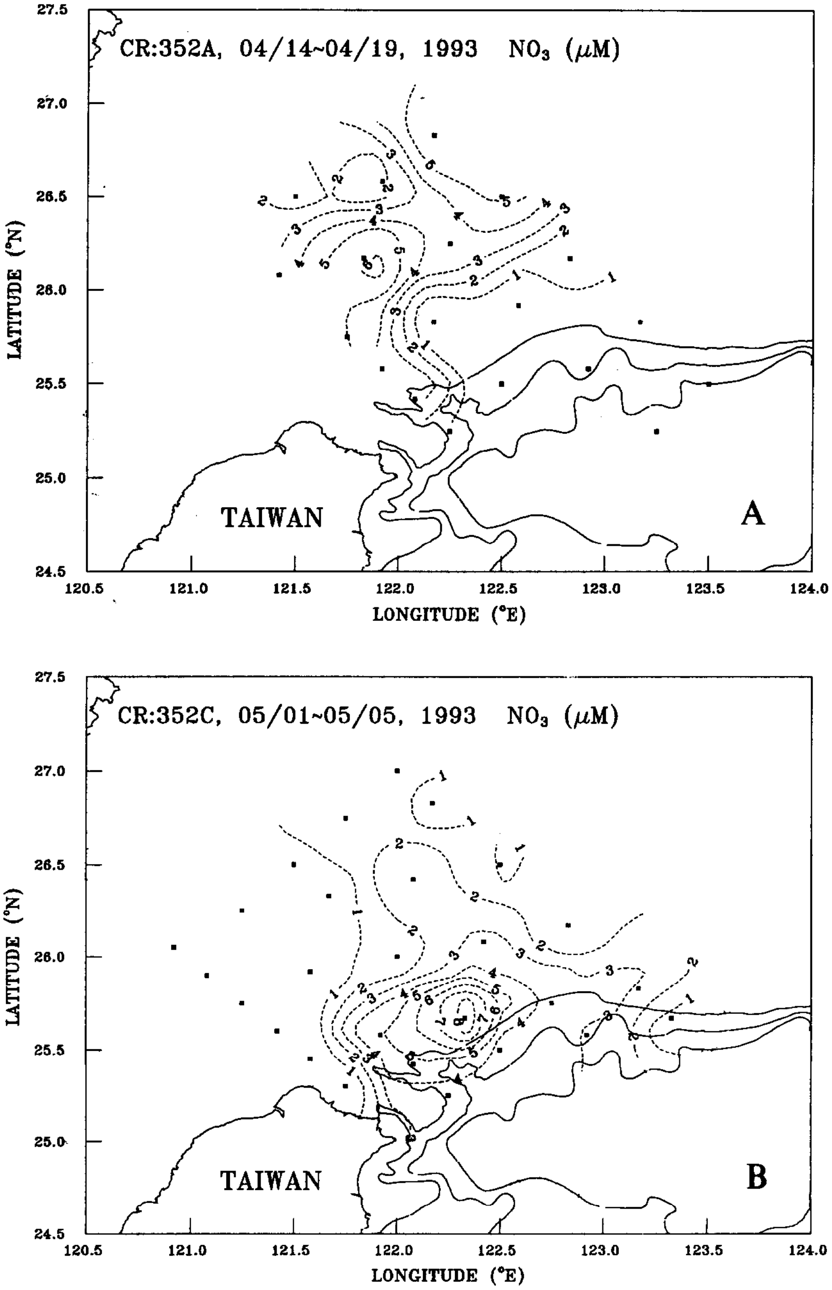

Fig. 5. Concentration of nitrate at 50 m and euphotic zone integrated Chl*a* (ICHLA) during cruises 352A and 352C.

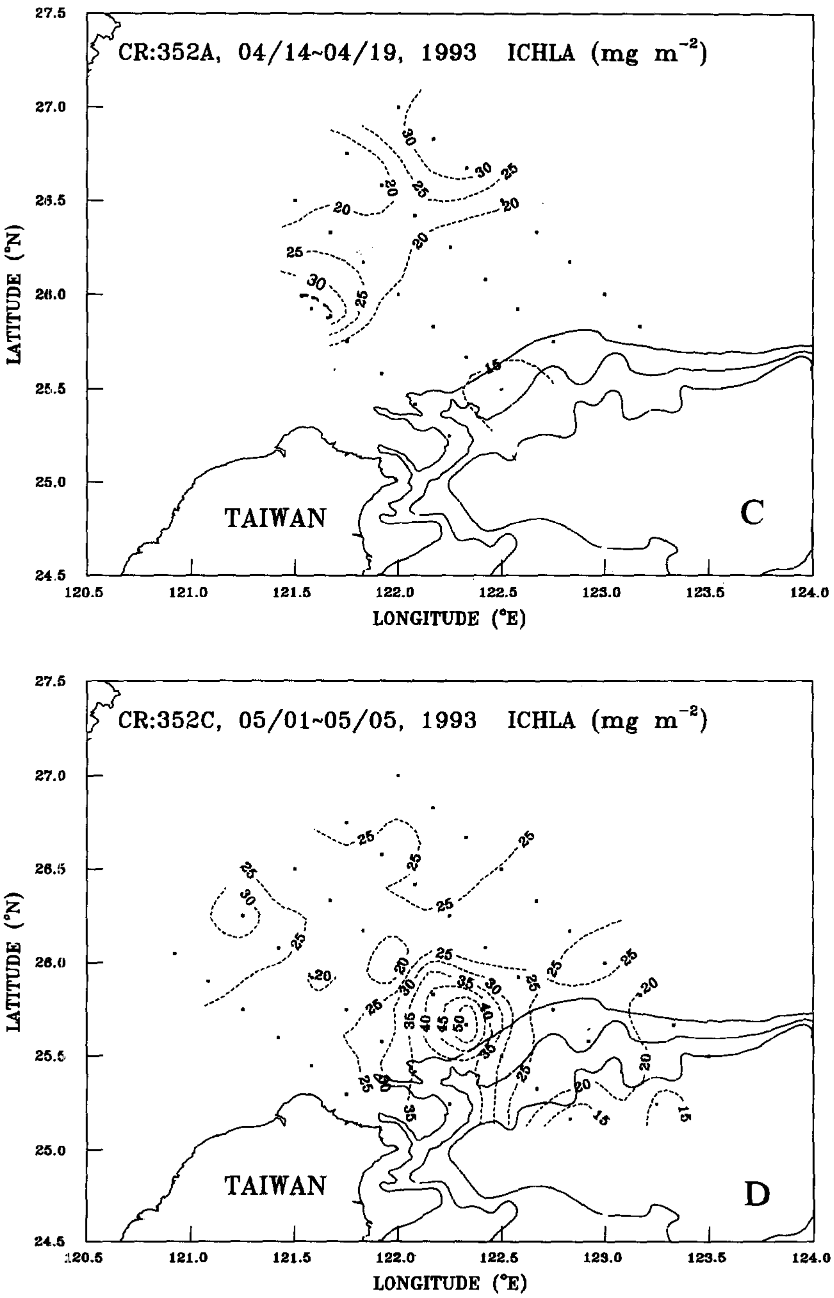

Fig. 5. (*Continued*)

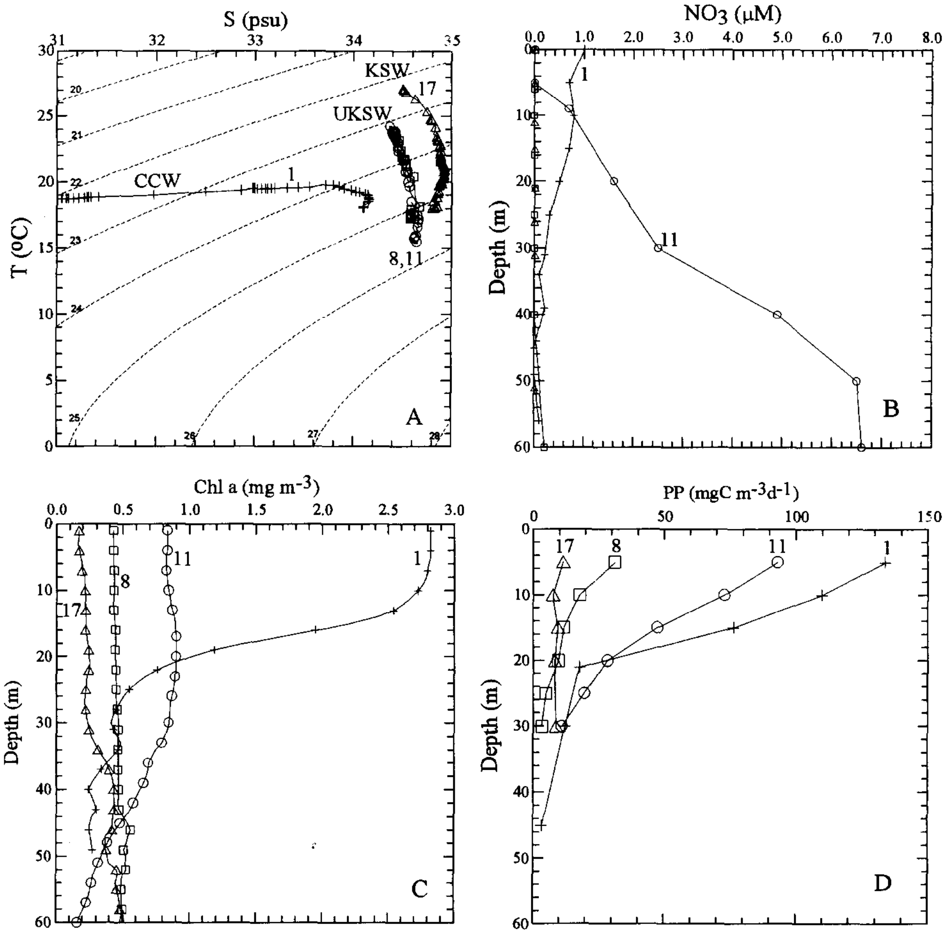

Fig. 6. Hydrographic and biological parameters on stations 1 (+), 8 (■), 11 (O) and 17 (Δ) during cruise 386: (A) temperature–salinity diagram; (B) nitrate concentrations; (C) Chl*a* concentrations and (D) primary productivity.

upwelled Kuroshio subsurface water displaced northwestward by the Kuroshio intrusion. In May 1994, primary productivity measurement were conducted in three water masses, which were the mainland China coastal water, the Kuroshio upwelling water and the Kuroshio water. In the upwelling waters, high Chl*a* concentration was apparently caused by the ample nitrate supply from the subsurface and enhanced primary production in the euphotic zone.

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