TAO, Vol.6, No.4, 607-620, September 1995

Temporal and Spatial Changes of Chlorophyll *a* in the KEEP Study Waters off Northern Taiwan

YUH-LING LEE CHEN[1]

(Manuscript received 21 Septermber 1994, in final form 6 May 1995)

ABSTRACT

The distribution data of chlorophyll *a* collected from 11 cruises between 1990-1993 in the KEEP study area was analyzed to demonstrate its temporal and spatial changes. Chlorophyll *a* concentration in the euphotic layer was generally low in March (0.02-0.67 mg.m^{-3}) and high in November (0.02-3.79 mg.m^{-3}). Sampling stations showed the highest chlorophyll *a* concentration during each cruise was mostly in the water along the brim of the East China Sea continental shelf, thus, indicating an association between the upwelling and bottom topography. Surface chlorophyll *a* concentration was negatively related to surface water temperature on all cruises. The distribution of the low surface water temperature was mostly caused by the upwelling. In winter, however, the shelf was flooded with cold water from the north, and the chlorophyll *a* concentration was low. The strength and the position of the center of the upwelling affected the dynamics of the chlorophyll *a* concentration. When the upwelling strength was not strong enough to reach water surface, the surface chlorophyll *a* concentration at the upwelling stations remained low. A significant negative relationship between the surface water temperature and the chlorophyll *a* concentration in all stations still existed because the chlorophyll *a* concentration in the warm Kuroshio water was even lower than in other regions. Dynamic temporal and spatial variations in chlorophyll *a* distribution were observed at the upwelling center surveyed repeatedly at one-week intervals. The vertical distribution of chlorophyll *a* showed a shallow subsurface maximum between 0 and 25 m in the upwelling region in contrast to between 50 and 75 m in the Kuroshio water. Surface chlorophyll *a* and the 0-100 m integrated chlorophyll *a* concentrations showed significantly positive correlations during nine out of the eleven cruises.

(Key words: Chlorophyll, KEEP, Upwelling)

---

[1] Department of Marine Resources, National Sun Yat-Sen University, Kaohsiung, Taiwan, R.O.C.

1. INTRODUCTION

The water on the continental shelf off northeastern Taiwan has long been a major fishing ground for both demersal and pelagic fishes. A permanent upwelling caused by the intrusion of the meandering Kuroshio Current into the continental shelf of the East China Sea has been reported (Liu *et al.*, 1992) in the area. Accordingly, cold and nutrient-laden water has been observed at the shelf break (Liu *et al.*, 1992). High concentrations of chlorophyll a have occurred in summer (Chen, 1992) as well as in winter (Chen, 1994) in the upwelling region.

Chlorophyll a distribution has been regarded as an important index for the estimation of phytoplankton biomass and the capacity of its primary production. Inorganic nutrients, especially nitrate, are often a limiting factor constraining the growth of phytoplankton in the euphotic zone in subtropical and tropical oceans (Lalli and Parsons, 1993). Upwelling is, thus, one of the principal causes of nutrients coming up to the euphotic zone from deeper the water in these areas.

A 5-year (1989-1993) integrated research project, the Kuroshio Edge Exchange Processes (KEEP), was initiated to study the dynamics of the physical, chemical and biological aspects of oceanography in describing the exchange processes of the mixing waters between the Kuroshio Current and the East China Sea continental shelf. The present report summarizes the spatial and temporal changes of chlorophyll a concentration in the aforementioned waters based on the results of 11 cruises conducted from 1990-1993. The effects of upwelling and the related parameters on the chlorophyll distribution were emphasized to provide a better understanding of the mechanisms of the distribution and, thus, for better numeric prediction.

2. MATERIALS AND METHODS

During the 1990-93 period, oceanographic studies including chlorophyll a measurements were conducted on 20 cruises in the KEEP study area. Complete data sets were obtained from 11 of the cruises. These observations covered every month of the year except for January, February, June and August. On all cruises, samples for the determination of chlorophyll a concentrations were collected from the *R/V Ocean Researcher I* using a rosette multi-sampler attached to a CTD probe. Two replicated 1-liter water samples were taken from 0, 3, 10, 25, 50, 75 and 100 m. Filtration was conducted on board using Whatman GF/F glass-fiber or GF/C filters under low vacuum (< 100 mm Hg). The filtered membranes were kept frozen in darkness at -20°C until analyses. Chlorophyll a concentration was measured according to the method of Strickland and Parsons (1972) for extracted samples using a fluorescence spectrophotometer. Integrated water column chlorophyll a concentration (Chl-a, mg.m^{-2}) to 100-m depth was calculated from the following equation:

$$Chl-a = \Sigma^{100m}(C_{i+1} + C_i)(D_{i+1} - D_i)/2,$$

where C_i and C_{i+1} are the chlorophyll a concentrations (mg.m^{-3}), and D_i and D_{i+1} are the depths of the upper and lower limit of sample i.

The data of water temperatures and nitrate concentrations from the Chemical Oceanography Data Bank of the National Science Council *R. V. Ocean Researcher I*, Regional Instrument Center, were used in the statistical analyses. Because the nomenclature of the same sampling station varied on different cruises, new names were assigned to all stations studied. A total of 55 stations were identified, and their localities together with their original names on each cruise are depicted in Table 1. These stations covered the main area that was thoroughly studied in detail during different phases of the KEEP project.

Table 1. Locations of the sampling stations and their original station names on respective cruises of the *R/V Ocean Researcher I.*

Station	Location (N)	(E)	Original Station Name	Station	Location (N)	(E)	Original Station Name
1	26°20'	120°30'	1[#]	29	25°40'	122°15'	20[#]
2	26°15'	120°40'	2[#]	30	25°05'	122°16'	512A[*]
3	26°10'	120°50'	3[#]	31	25°00'	122°20'	26[#], 5022[*]
4	26°05'	121°00'	4[#]	32	25°25'	122°20'	12[#]
5	26°00'	121°10'	5[#]	33	25°40'	122°20'	32[+], 5422[*]
6	26°15'	121°15'	21[+]	34	25°50'	122°20'	21[#]
7	25°55'	121°20'	6[#]	35	25°34'	122°24'	542A[*]
8	25°50'	121°30'	7[#], 5513[*]	36	25°10'	122°25'	27[#]
9	26°30'	121°30'	37[+]	37	25°35'	122°25'	24[#]
10	25°40'	121°37'	5414[*]	38	26°05'	122°25'	42[+]
11	25°45'	121°40'	8[#]	39	25°45'	122°30'	25[#]
12	26°45'	121°45'	38[+]	40	25°30'	122°30'	31[+], 5323[*]
13	26°10'	121°50'	6115[*]	41	25°20'	122°30'	13[#]
14	25°40'	121°50'	9[#]	42	24°50'	122°30'	4523[*]
15	25°30'	121°50'	5315[*]	43	25°30'	122°35'	28[#]
16	25°35'	121°55'	25[+]	44	25°55'	122°35'	43[+]
17	25°59'	122°00'	6020[*]	45	25°40'	122°40'	29[#]
18	25°35'	122°00'	10[#]	46	25°20'	122°40'	5224[*]
19	25°20'	122°00'	5220[*]	47	25°15'	122°40'	14[#]
20	25°10'	122°00'	18[#]	48	24°40'	122°40'	4424[*]
21	25°20'	122°05'	19[#]	49	25°45'	122°45'	44[+]
22	25°25'	122°05'	26[+]	50	25°10'	122°50'	15[#], 5125[*]
23	25°50'	122°10'	33[+], 5521[*]	51	25°05'	123°00'	16[#]
24	25°30'	122°10'	11[#]	52	25°00'	123°00'	28[+], 5030[*]
25	25°10'	122°10'	5121[*]	53	24°50'	123°10'	4531[*]
26	25°05'	122°10'	22[#]	54	25°00'	123°10'	17[#]
27	25°15'	122°15'	23[#], 27[+]	55	25°15'	123°15'	47A[+]
28	25°28'	122°15'	11A[#]				

[#] Cruises 304, 323, 352B, 352D & 373

[+] Cruises 330B & 331A

[*] Cruises 254, 260, 261, 271 & 280

3. RESULTS AND DISCUSSION

Chlorophyll *a* concentration in the study waters dynamically changed spatially and temporally. In the euphotic layer, the minimum value (0.02-0.67 mg.m^{-3}) was observed in March (OCI-271) and the maximum (0.02-3.79 mg.m^{-3}) in November (OCI-260). Surface (0 m) chlorophyll *a* concentration ranged from 0.03 to 3.79 mg.m^{-3} with higher values occurring in November and December and lower values (0.04-0.14 mg.m^{-3}) in July. The Kuroshio water had the lowest chlorophyll *a* concentrations among all stations on each cruise ranging between 0.03-0.16 mg.m^{-3} on the surface and 5.93-23.34 mg.m^{-2} on the upper 100 m when stations 53, 54 and 55 were used as representative. Often the highest chlorophyll *a* concentrations of all stations on each cruise occurred at the shelf break, while an intermediate chlorophyll *a* concentration occurred in the shelf water.

When surface chlorophyll *a* concentrations of all stations on the 11 cruises were correlated with surface water temperatures, significant negative relationships were observed (Table 2), indicating that the region with low surface water temperature had a high chlorophyll *a* concentration. Surface water temperature in the study area ranged from 16.7 to 28.9°C. Temperature alone could explain 22-80% of the variations in chlorophyll *a* concentration (Table 2). The low surface water temperatures probably represent the upwelling phenomenon in most seasons and the coastal continental cold water in winter (cruise 271, Chen, 1994), whereas, the negative relationship of surface water temperature and the chlorophyll *a* concentration may also be reinforced or simply due to the low chlorophyll *a* concentration in the warm Kuroshio water. The latter was observed in Cruise 323 (Table 2) when the upwelled water was not brought up to the surface (Figure 1). The surface chlorophyll *a* concentrations, therefore, remained at low levels ranging from 0.04-0.14 $mg.m^{-3}$ in the study stations (Figure 2). The upper 100 m chlorophyll *a* concentrations were also very low (8.56-36.48 $mg.m^{-2}$).

Table 2. Relationships of surface chlorophyll *a* concentration (Chl) and surface water temperature (Temp) observed between September 1990 and May 1993.

Date (Cruise)	Chl ($mg{\cdot}m^{-3}$)	Temp (°C)	Regression equation	R^2	p
March 91 (271)	0.07-0.67	16.7-25.0	$Chl=-8.652+0.911\ Temp -0.023\ Temp^2$	0.74	<0.01
April 93 (352B)	0.31-1.76	19.4-25.1	Chl=5.048-0.184 Temp	0.42	0.02
May 93 (352D)	0.14-0.70	19.2-26.6	Chl=1.517-0.044 Temp	0.28	0.01
May 91 (280)	0.10-1.01	20.9-26.3	Chl=3.656-0.130 Temp	0.60	<0.01
July 91 (323)	0.04-0.14	26.6-28.5	Chl=0.827-0.027 Temp	0.27	0.01
September 90 (254)	0.03-0.99	22.2-27.7	Chl=1.997-0.065 Temp	0.22	0.04
September 92 (330B)	0.04-1.23	24.1-28.9	Chl=6.26-0.223 Temp	0.66	<0.01
October 92 (331A)	0.04-0.61	24.4-27.4	Chl=4.587-0.167 Temp	0.58	<0.01
November 90 (260)	0.12-3.79	21.2-26.7	Chl=9.135-0.333 Temp	0.33	0.01
November 90 (261)	0.20-1.36	21.8-25.8	Chl=5.504-0.202 Temp	0.80	<0.01
December 91 (304)	0.28-2.46	20.1-24.3	Chl=6.307-0.248 Temp	0.24	0.04

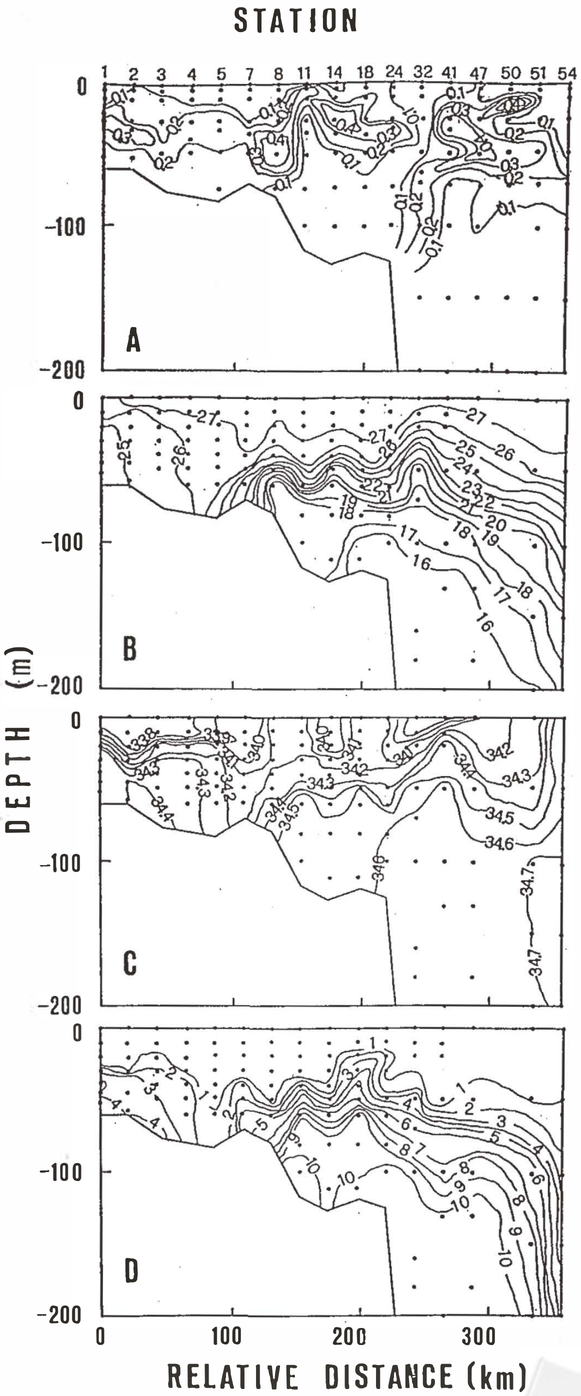

Fig. 1. Cross-sections of (A) chlorophyll *a* (mg.m^{-3}), (B) temperature (°C), (C) salinity ($^0/_{00}$) and (D) nitrate (M) in the study water surveyed during Cruise 323 (July 1992).

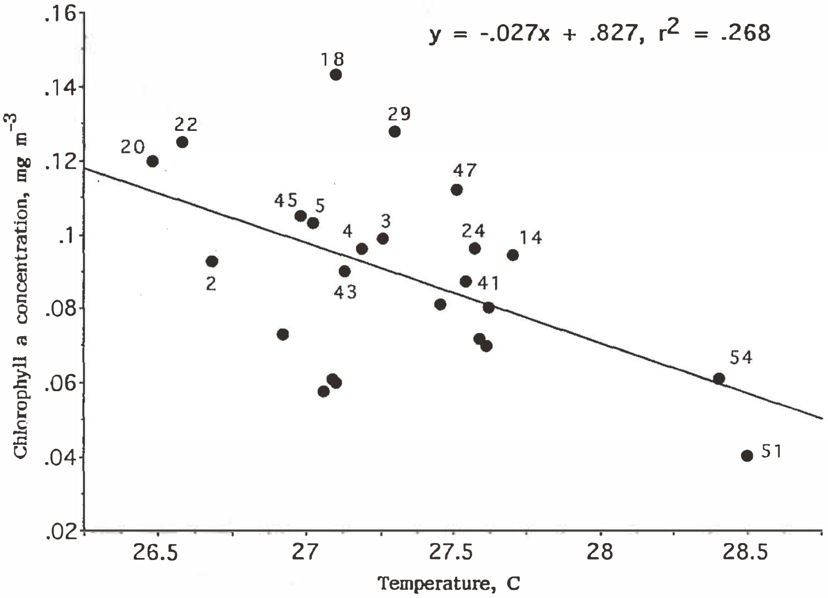

Fig. 2. Relationship of surface water temperatures and surface chlorophyll *a* concentrations collected on Cruise 323 (July 1992).

Among these low chlorophyll *a* concentrations, a significant negative relationship of surface chlorophyll *a* and surface water temperature still existed on the cruise due to the very low chlorophyll *a* concentration in the warm Kuroshio water (Figure 2). The result of this cruise also elucidated the importance of the upwelled strength. And the abundance of inorganic nutrients to the phytoplankton biomass is especially critical in the euphotic surface water.

The relationship between surface chlorophyll *a* concentration and surface NO_3-N level (Table 3) was, however, not as consistent as that between surface chlorophyll *a* concentration and temperature. In these events, when significant correlations could be established (March, April, May and September), high NO_3-N concentrations were accompanied by high chlorophyll *a* concentrations. No such correlations were established otherwise. It seems that temperature was generally a more indicative factor than was the NO_3-N concentration in estimating the distribution of phytoplankton biomass. NO_3-N is regarded as the most limiting nutrient to regulate phytoplankton growth in most oceanic regions (Ryther and Dunstan, 1971; Goldman, 1975). The negative relationship between chlorophyll *a* concentration and temperature was most likely to have been caused by the effects of the upwelling (Chen, 1992). The cold but nutrient-laden upwelled water supported the growth of phytoplankton. The status of blooming, on the other hand, was decided by the maturation stages of the upwelling (Takahashi *et al.*, 1986). In winter, nutrient-laden cold water from the north flooded the shelf, and the chlorophyll *a* concentration on the shelf was lower than that on the shelf break (Chen, 1994). Thus, besides nutrients, many other factors, such as grazing activity (Frost, 1991), concentration of trace metals (Martin *et al.*, 1990; Minas and Minas, 1992), water temperature, light extinction rate and turbulence (Jacques and Minas, 1981) might have worked individually or together to affect the chlorophyll *a* concentrations. The variation of the determination of coefficients (R^2) among cruises (Table 3) also reflected these possibilities.

Table 3. Relationships between surface chlorophyll *a* concentration (Chl) and nitrate concentration (NO_3) observed between September 1990 and May 1993.

Date (Cruise)	Regression equation	R^2	p	n
March 91 (271)	$Chl=0.18+0.041\ NO_3$	0.41	0.003	19
April 93 (352B)	$Chl=0.196+1.178\ NO_3$	0.70	<0.001	12
May 93 (352D)	Not significant			21
May 91 (280)	$Chl=0.405+0.134\ NO_3$ $Chl=0.280+0.506\ NO_3-0.106\ NO_3^2$	0.28 0.50	0.020 0.004	19
July 92 (323)	Not significant			22
September 90 (254)	$Chl=0.233+0.133\ NO_3$ $Chl=0.160+0.703 NO_3-0.161 NO_3^2$	0.37 0.59	0.006 <0.001	19
September 92 (330B)	Not significant			14
October 92 (331A)	Not significant			12
November 90 (260)	Not significant			19
December 91 (304)	Not significant			18

Stations with chlorophyll *a* concentration higher than 80% of the maximum value obtained in all stations in each cruise were located mostly at the brim of the continental shelf (Figure 3) where the bottom depth was between 100 and 200 m. Several stations had such a high chlorophyll *a* concentration on more than 2 cruises. They were all located along the brim of the shelves (the Chilung Shelf and the East China Sea Shelf) and canyons (the Mien-Hua Canyon and the North Mien-Hua Canyon, Figure 4). This indicates that the upwelling mechanism is probably closely associated with the bottom topography when the Kuroshio water intrudes the shelf. And the strength of the upwelling and/or the location of the upwelling center seem to vary from time to time around the brim of the shelf where a permanent upwelling system was reported (Chern *et al.*, 1990). The representative high chlorophyll *a* concentrations in the upwelled water around the shelf brim in November are shown in Figure 5. Similar phenomena for different seasons have been reported elsewhere (August and September in Chen 1992, March in Chen 1994).

Chlorophyll *a* concentrations in the shelf waters were usually between those of the Kuroshio and the shelf break. Occasionally, they were higher than that of the shelf break. During Cruise 260, the shelf stations (Stations 8 and 13) had higher surface chlorophyll *a*

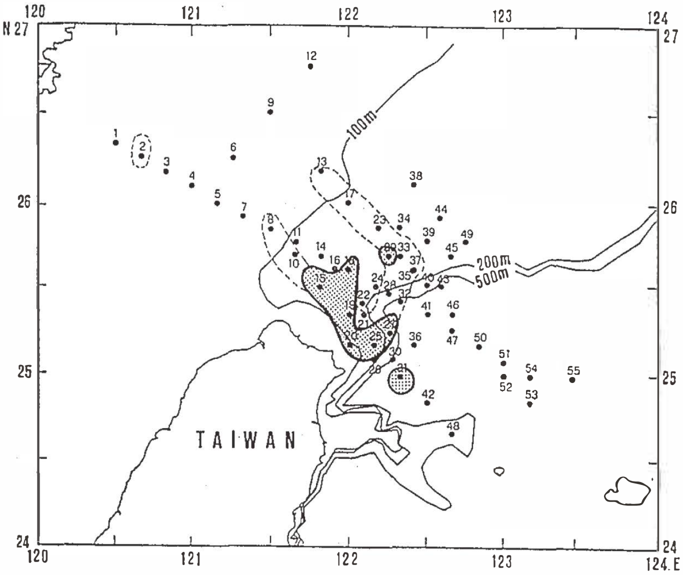

Fig. 3. Location of the study site off the northeastern coast of Taiwan. Numbers indicate sampling stations. Stations having at least once a surface chlorophyll *a* concentration higher than 80% of the maximum value obtained at all stations on each cruise are circled within the dashed line. Among these, those having such high chlorophyll *a* concentration in more than two cruises are stippled.

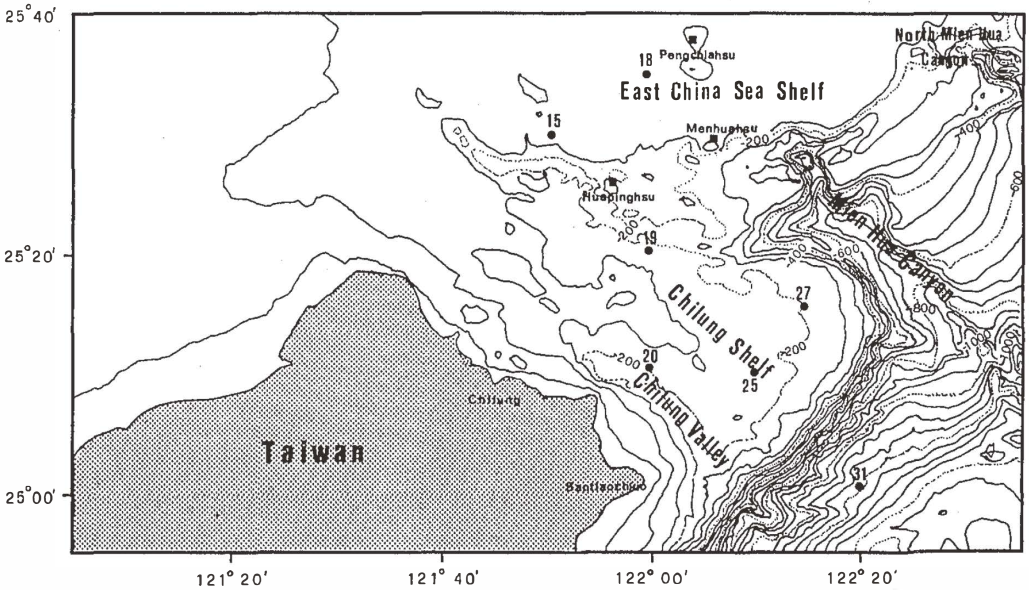

Fig. 4. Locations of sampling stations (●) (more than 2 of the 11 cruises surveyed) which had surface chlorophyll *a* concentrations higher than 80% of the maximum value obtained at all stations during each cruise. Background bathymetry map is the courtesy of Dr. G. Song, Institute of Oceanography, National Taiwan University, Taipei, Taiwan.

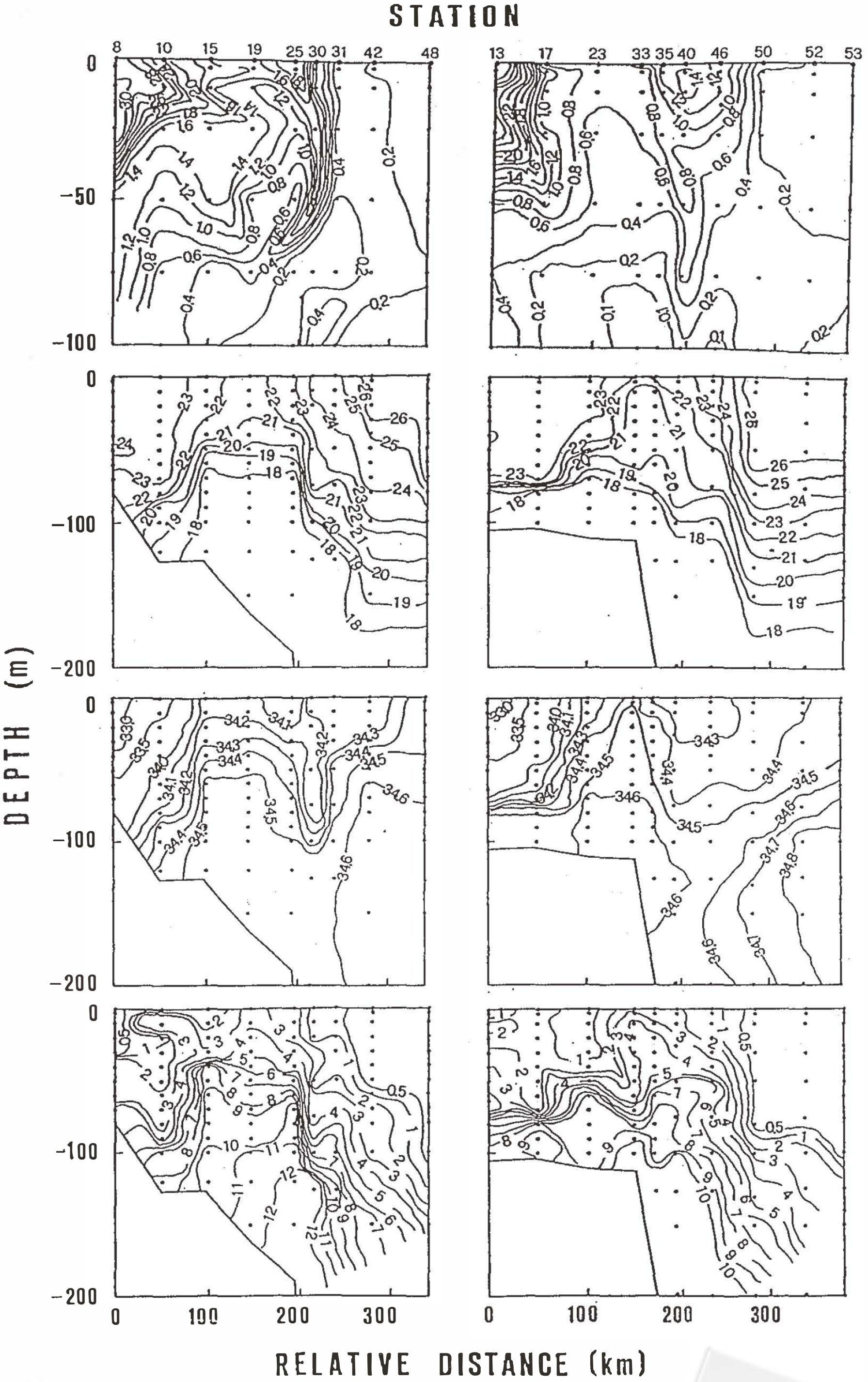

Fig. 5. Cross-sections of (A) chlorophyll a (mg.m^{-3}), (B) temperature (°C), (C) salinity ($^{0}/_{00}$), and (D) nitrate (μM) in the study water surveyed during Cruise 260 (November 1990).

concentrations (3.79 and 3.02 mg.m^{-3}) and integrated upper 100 m chlorophyll *a* concentrations (139.9 and 218.8 mg.m^{-2}) than those of Station 19 at the shelf break (surface concentration: 1.60 mg.m^{-3} and integrated upper 100 m concentration: 84.6 mg.m^{-2}). The upwelling phenomenon was clearly observed at the shelf break (Figure 5) during this cruise, with low surface water temperature (21.59°C) and high nitrate concentration (3.37 μM). In contrast, shelf stations (Stations 8 and 13) had both relatively higher surface water temperatures (23.14-23.40°C) and lower nitrate concentrations (0.43-0.8 μM). The mechanism of this high chlorophyll *a* concentration with low nitrate concentration at the shelf water warrants further study.

Although chlorophyll *a* concentration at the shelf break was usually higher than in the Kuroshio and the shelf waters, the chlorophyll *a* concentration at the shelf break varied with time. For example, in March the surface and the upper 100 m chlorophyll *a* concentraitons at the shelf break were 0.67 mg.m^{-3} and 31.79 mg.m^{-2}, respectively (Station 19, Cruise 271), while in November they were up to 2.28 mg.m^{-3} and 66.5 mg.m^{-2} (Station 25, Cruise 260) and 0.88 mg.m^{-3} and 122.6 mg.m^{-2} (Station 30). These great temporal changes in chlorophyll *a* concentrations could also be manifested by comparing observations conducted during two consecutive cruises (Cruises 260 and 261) with a one-week interval. The surface chlorophyll *a* concentration at Station 19 dropped from 1.60 to 0.59 mg.m^{-3} and at Station 35 from 1.29 to 0.47 mg.m^{-3}, respectively as the upwelled center moved northwestwardly from Stations 19 and 35 (Figure 5) toward a new center closer to the shelf at Stations 10 and 23 (Figure 6). Thus, not only the dynamics of the upwelling strength but also the meandering of the upwelling center spatially and temporally affected the chlorophyll *a* distribution.

The vertical distribution of chlorophyll *a* in the study area showed a shallow subsurface maximum between 0 and 25 m in the upwelling region, while it was between 50-75 m in the Kuroshio water (Figure 7 and Chen, 1992). A similar vertical distribution with shallow subsurface maximum was observed at the shelf when its chlorophyll *a* concentration was high (Figure 8). Chlorophyll *a* is apt to develop a maximum near the surface in eutrophic waters and at greater depths in oligotrophic waters (Ichimura, 1956). Regression analysis between integrated water column chlorophyll *a* concentration and respective surface chlorophyll *a* concentration in the present study indicates, in general, a positive relationship between the two (Table 4). Surface chlorophyll *a* concentration, accordingly, can be effectively (21%-72% of the variation explained) used to estimate the water column chlorophyll *a* concentration which estimates all phytoplankton biomass in a water column.

The good correlations between surface water temperature and surface chlorophyll *a* concentration and between surface chlorophyll and integrated chlorophyll imply a possible direct link between surface temperature and integrated water column chlorophyll. The regression analysis of the two variables indicates good correlations (Table 5). The fact that these regression coefficients are lower than those between surface and integrated water column chlorophyll indicates that the surface chlorophyll concentration is still a better parameter than surface temperature in estimating water column phytoplankton biomass.

The present results pinpoint the possible usefulness of surface water temperature in predicting phytoplankton biomass distribution in the study waters. Some precautions, however, need to be taken before this application can be realized because not all of the regression coefficients in the present analyses showed consistent patterns. Further efforts must be made to obtain more concise observations. The role of nitrate, its interaction with temperature and other factors, such as grazing activity, have to be investigated quantitatively. In doing so, the understanding of phytoplankton distribution, both in space and in time, in response to the dynamic changes in the study waters will be enhanced.

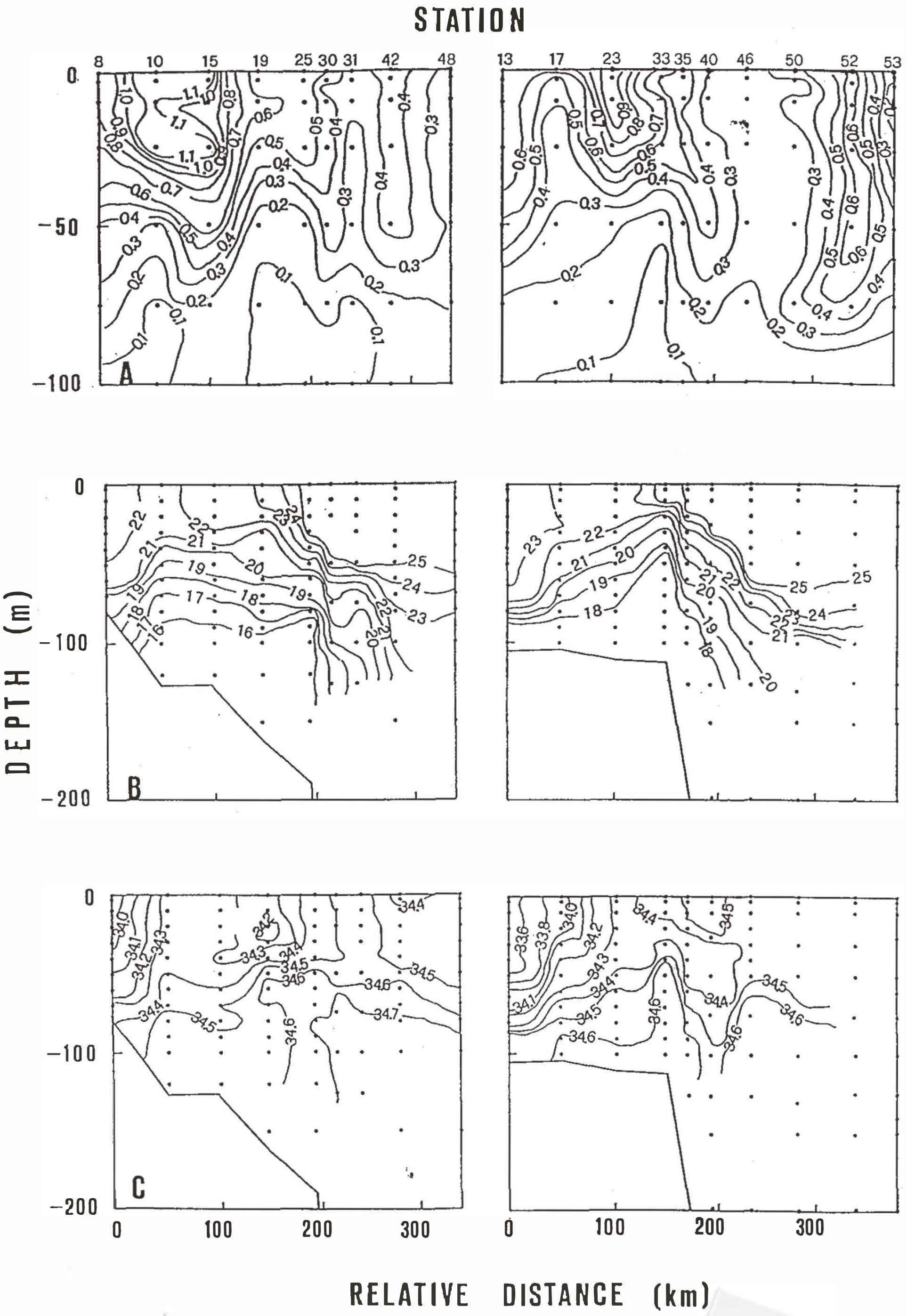

Fig. 6. Cross-sections of (A) chlorophyll a (mg.m-3), (B) temperature (°C), and (C) salinity ($^0/_{00}$) in the study water surveyed during Cruise 261 (November 1990).

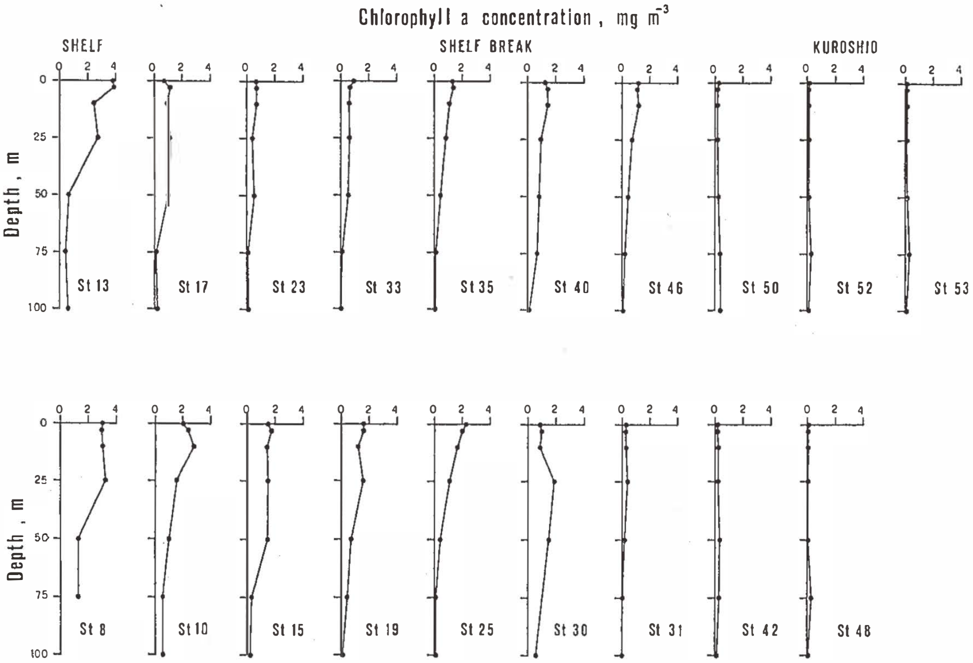

Fig. 7. Vertical distribution of chlorophyll a concentration (mg.m^{-3}) obtained during Cruise 271 (March 1991).

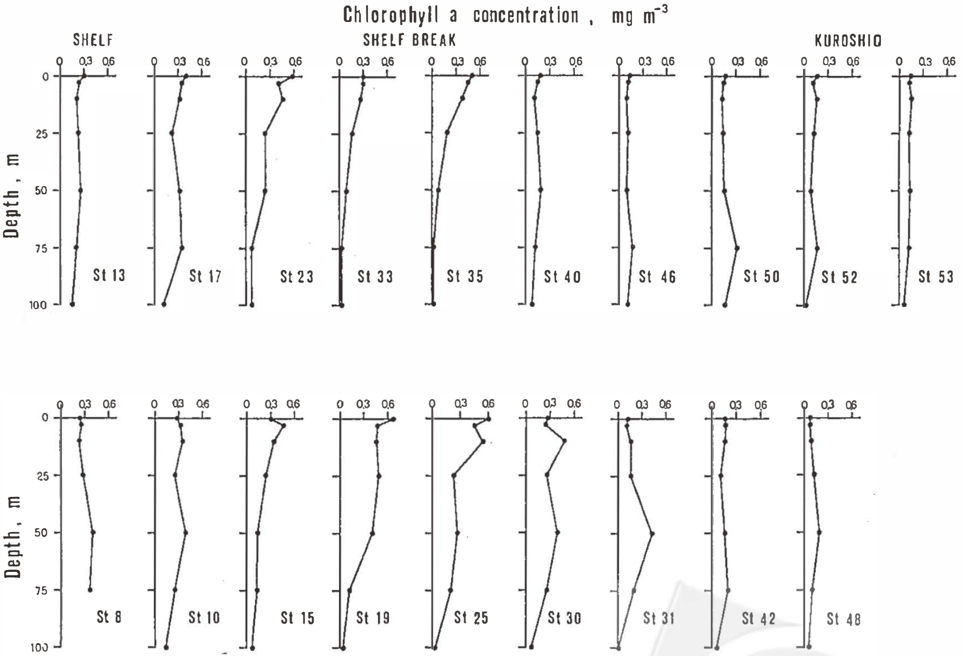

Fig. 8. Vertical distribution of chlorophyll a concentration (mg.m^{-3}) measured during Cruise 260 (November 1990).

Table 4. Relationships between surface chlorophyll *a* concentration (Chl) and chlorophyll *a* concentration integrated over the upper 100 m ($\Sigma \mathrm{Chl}_{100m}$) obtained between September 1990 and May 1993.

Date (Cruise)	Regression Equation	R^2	p	n
March 91 (271)	$\Sigma\ \mathrm{Chl}_{100m}=13.86+19.991\ \mathrm{Chl}$	0.21	0.047	19
April 93 (352B)	$\Sigma\ \mathrm{Chl}_{100m}=14.196+81.399\ \mathrm{Chl}-36.274\ \mathrm{Chl}^2$	0.52	0.027	13
May 93 (352D)	Not significant			21
May91 (280)	$\Sigma\ \mathrm{Chl}_{100m}=14.195+38.999\ \mathrm{Chl}$	0.72	<0.001	19
July 92 (323)	Not significant			22
September 90 (254)	$\Sigma\ \mathrm{Chl}_{100m}=25.484+45.071\ \mathrm{Chl}$	0.39	0.005	19
September 92 (330B)	$\Sigma\ \mathrm{Chl}_{100m}=16.407+45.595\ \mathrm{Chl}$	0.56	0.002	14
October 92 (331A)	$\Sigma\ \mathrm{Chl}_{100m}=8.238+38.415\ \mathrm{Chl}$	0.43	0.020	12
November 90 (260)	$\Sigma\ \mathrm{Chl}_{100m}=19.745+42.899\ \mathrm{Chl}$	0.68	<0.001	19
November 90 (261)	$\Sigma\ \mathrm{Chl}_{100m}=14.275+32.500\ \mathrm{Chl}$	0.70	<0.001	18
December 91 (304)	$\Sigma\ \mathrm{Chl}_{100m}=11.964+34.274\ \mathrm{Chl}$	0.75	<0.001	18

Table 5. Relationships between chlorophyll a concentration integrated over the upper 100 m ($\Sigma\ \mathrm{Chl}_{100m}$) and surface water temperature (Temp) obtained between September 1990 and May 1993.

Date (Cruise)	Regression Equation	R^2	p	n
March 91 (271)	$\Sigma\ \mathrm{Chl}_{100m}=53.807-1.58\ \mathrm{Temp}$	0.46	<0.01	19
April 93 (352B)	Not significant			13
May 93 (352D)	Not significant			21
May 91 (280)	$\Sigma\ \mathrm{Chl}_{100m}=171.485-5.696\ \mathrm{Temp}$	0.54	<0.01	19
July 92 (323)	$\Sigma\ \mathrm{Chl}_{100m}=191.76-6.404\ \mathrm{Temp}$	0.23	0.02	22
September 90 (254)	Not significant			19
September 92 (330B)	$\Sigma\ \mathrm{Chl}_{100m}=391.201-13.435\ \mathrm{Temp}$	0.64	<0.01	14
October 92 (331A)	$\Sigma\ \mathrm{Chl}_{100m}=196.991-6.899\ \mathrm{Temp}$	0.29	0.07	12
November 90 (260)	$\Sigma\ \mathrm{Chl}_{100m}=402.641-13.904\ \mathrm{Temp}$ $\Sigma\ \mathrm{Chl}_{100m}=-5118.071+445.373\ \mathrm{Temp}-9.503\ \mathrm{Temp}^2$	0.21 0.43	0.05 0.01	19
November 90 (261)	$\Sigma\ \mathrm{Chl}_{100m}=193.733-6.575\ \mathrm{Temp}$	0.57	<0.01	18
December 91 (304)	$\Sigma\ \mathrm{Chl}_{100m}=247.817-9.379\ \mathrm{Temp}$	0.22	0.05	18

Acknowledgments Gratitude is extended to G. C. Gong and S. Tsai who measured the nitrate data used in the statistical analysis. The author is also appreciative of the cooperation of the captain and crew of the *R/V Ocean Researcher I* during the sampling. Y. Wong, W. H. Lee and E. H. Lin assisted in the sample collection and chlorophyll *a* analysis. This research was supported by the National Science Council of the Republic of China through research grants: NSC 79-0209-M110-03, NSC 80-0209-M110-03, NSC 81-0209-M110-07 and NSC 82-0209-M110-040K.

REFERENCES

Chen, Y. L. L., 1992: Summer phytoplankton community structure in the Kuroshio Current-related upwelling northeast of Taiwan. *TAO*, **3**, 305-320.

Chen, Y. L. L., 1994: The importance of temperature and nitrate to the distribution of phytoplankton in the Kuroshio-induced upwelling northeast of Taiwan. *Proc. Natl. Sci. Council (ROC)-Part B*, **18**, 44-51.

Chern, C. S., J. Wang, and D. P. Wang, 1990: The exchange of Kuroshio and East China Sea shelf water. *J. Geophys. Res.*, **95**, 16017-16023.

Frost, B. W., 1991: The role of grazing in nutrient-rich areas of the open sea. *Limnol. Oceanogr.*, **36**, 1616-1630.

Goldman, J. C., 1975: Identification of nitrogen as a growth limiting nutrient in waste waters and coastal marine waters through continuous culture algal assays. *Water Res.*, **10**, 97-104.

Ichimura, S., 1956: On the standing crop and productive structure of phytoplankton community in some lakes of central Japan. *Bot. Mag. Tokyo*, **69**, 7-16.

Jacques G., and M. Minas, 1981: Production primaire dans le secteur indien de l'Ocean Antarctique en fin d'ete. *Oceanol. Acta*, **4**, 33-41.

Lalli, C. M., and T. R. Parsons, 1993: Biological Oceanography: An Introduction, Pergamon Press, Oxford, 301pp..

Liu, K.-K., G.-C. Gong, S. Lin, C.-Y. Yang, C.-L. Wei, S.-C. Pai, and C.-K. Wu, 1992: The year-round upwelling at the shelf break near the northern tip of Taiwan as evidenced by chemical hydrography. *TAO*, **3**, 243-276.

Martin, J. H., S. E. Fitzwater, and R. M. Gordon, 1990: Iron deficiency limits phytoplankton growth in Antarctic waters. *Glob. Biogeochem. Cycles*, **4**, 5-12.

Minas, H. J., and M. Minas, 1992: Net community production in "High Nutrient-Low Chlorophyll" waters of the tropical and Antarctic Oceans: grazing vs iron hypothesis. *Oceanol. Acta*, **15**, 145-162.

Ryther, J. H., and W. M. Dunstan, 1971: Nitrogen, phosphorus, and eutrophication in the coastal marine environment. *Science*, **171**, 1008-1013.

Strickland, J. D. H., and T. R. Parsons, 1972: A Practical Handbook of Seawater Analysis. *Bull. Fish. Res. Bd. Canada*, **167**, 1-310.

Yamaguchi, Y. Fujita, and S. Ichimura, 1986: Temporal change in nutrient concentrations and phytoplankton biomass in short time scale local upwelling around the Izu Pennisula, Japan. *J. Plankton Res.*, **8**, 1039-1049.