La mer 32: 195–207, 1994
Sociéte franco-japonaise d'océanographie, Tokyo

Distribution of Diatom Assemblages in and around a Warm Core Ring in the North Pacific Polar Frontal Zone*

Kuo Ping CHIANG**†, Akira TANIGUCHI** and Satoshi KATO**

Abstract: Distribution of diatom assemblages in the North Pacific Polar Frontal Zone east of northern Japan in late spring was investigated in relation to distribution of water types. By principal component analyses, nine diatom assemblages and five water types were defined. Patterns of distribution of the diatom assemblages and the water types were not always consistent with each other, probably because of more conservative nature of the diatom assemblages than physico-chemical properties of the water types. The most widely distributed diatom assemblage, which is named as the Background Assemblage, was mainly composed of neritic cosmopolitan species and was observed to be small in population density. Production of the diatom assemblages is likely to be enhanced in the surface layer when water types other than a background mixed water intrude and then the new assembalges are formed there.

1. Introduction

The Kuroshio flows along the south coast of Japan archipelago and turns around 36° N into the Kuroshio Extension flowing eastward. The latter forms the southern border of the North Pacific Polar Frontal Zone, which demarcates the frontal zone from the subtropical waters in south. When the Kuroshio Extension has an extensive meander to north, a warm core ring is sometimes pinched off and shifts to further north. On the other hand, the Oyashio is usually flows in far north and demarcates the frontal zone from the subarctic water in north by forming the Oyashio Front. In addition to these two currents a less prevailing Tsugaru Warm Current intrudes from the Japan Sea through the Tsugaru Straits into the western edge of the frontal zone and flows southward along the east coast of Sanriku District. Consequently, oceanographic conditions in the western part of the Polar Frontal Zone are very complicated due to the interaction of several different water masses such as warm and cold core rings and streamers, coastal Tsugaru warm water, and neritic water which are scattered over a so-called mixed water (*e.g.* KAWAI, 1972; KAWAI and SAITOH, 1986: NAGATA *et al.*, 1992). The last water mass, which is the final mixture of all the water masses listed just above, occupies widely and then forms a background water mass of the frontal zone. It has been pointed out that identification of these water masses by a conventional T-S analysis is difficult (HANAWA and MITSUDERA, 1987).

A low productive diatom assemblage which is composed mainly of neritic cosmopolitan species is almost homogeneously distributed in the mixed water and named the Background Assemblage in the Polar Frontal Zone (CHIANG and TANIGUCHI, 1993). This assemblage is likely to be formed by winter convection of water which selects a few tolerant species to winter conditions. It has been suggested that some other productive assemblages are formed during warm seasons on this Background Assemblage particularly at the Kuroshio Front and coastal front and in a cold ring (*e.g.* MARUMO and AMANO, 1956; MARUMO, 1967; YAMAMOTO *et al.*, 1981, 1988). Therefore, the distribution of diatom assemblages in warm seasons can indicate the origin of very slightly different water masses that can not be identified by the T-S analysis.

In this paper, we try to identify water masses of different origins in detail by principal

* Received July 20, 1994
** Laboratory of Biological Oceanography, Faculty of Agriculture, Tohoku University, Sendai, Miyagi 981, Japan
† Present address: Department of Fishery Science, National Taiwan Ocean University, Keelung 20224, Taiwan, R.O.C.

component analyses of diatom assemblages in the western Polar Frontal Zone. Possible enhancement of diatom productivity in the localities where different waters intrude into the background mixed water mass is suggested.

2. Materials and methods

Samples were collected on the Cruise KT-90-7 of R/V "Tansei Maru" of the Ocean Research Institute of the University of Tokyo (Fig. 1). The cruise was divided into two legs. Leg 1 was for samplings at Sts. C20–C22 arranged on a longitudinal section crossing a warm core ring and St. C18 as a reference station in the Kuroshio Extension. Leg 1 was carried out during the period from 29 May to 2 June 1990. Leg 2 was for samplings at Sts. C30–C35 on a section crossing the edge of the same warm core ring, and Sts. C40 and C59 as references in cold mixed water and the Oyashio. Leg 2 was done in 3-10 June 1990. The section through Sts. C19–C22 and a supplemental St. C40 is named Line A and that through Sts. C30–C35 is Line B below.

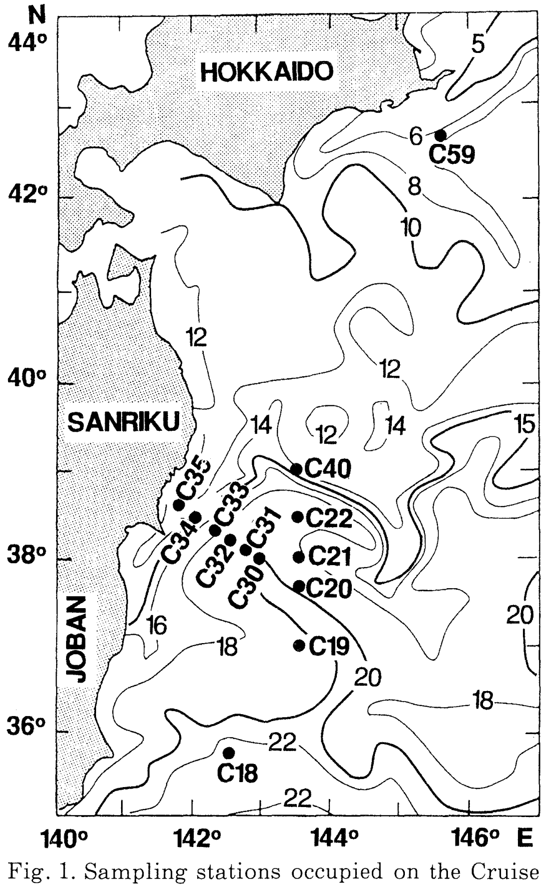

Fig. 1. Sampling stations occupied on the Cruise KT-90-7 to the western North Pacific Polar Frontal Zone during the period from 29 May to 10 June, 1990. Isotherms at the sea surface are adapted from the Japan Fisheries Information Service Center (1990)

Water samples were collected from 8–12 depths in the surface layer down to 75 m on Line A and down to 200 m on Line B. Methods of microscopic examination of diatom assemblages and chemical analyses of the nutrients such as dissolved silica, phosphate, nitrite, nitrate and ammonia were given in CHIANG and TANIGUCHI (1993).

To see relationships between diatom assmblages and water types in distribution, principal component analyses (PCAs) and cluster analyses (PIELOU, 1984) were done by using the oceanographic data set on temperature, salinity and five nutrients (PCA-OD) (Table 1) and the diatom data set. The latter was processed in the following two ways to reduce number of parameters reaching 160 species in total. At first, diatom species identified were grouped into 14 types according to their distributional characteristics (DC) reported in literature (KOKUBO, 1960, MARUMO *et al.*, 1966, YAMAJI, 1984) (Table 2). In the second way 24 common and dominant species (DS) which occurred in more than 50 % of samples were selected (Table 3). In the following sections, we describe the first as PCA-DC and the second as PCA-DS.

Position of the first principal component PC1 on X-axis and that of the second principal component PC2 on Y-axis in scatter diagrams of PC2 on PC1 were used to identify clusters of components by an average clustering method (Euclidean distance=0.6).

3. Results

3.1. *Water Types*

Line A: Data on the surface temperature over the sea areas around Japan gathered during the period from 1 to 5 June were compiled by the Japan Fisheries Information Service Center (Fig. 1). It gives general configuration of water masses at the surface around the day of the present sampling; the Kuroshio Extension which flowed eastward along the 22°C isotherm, a

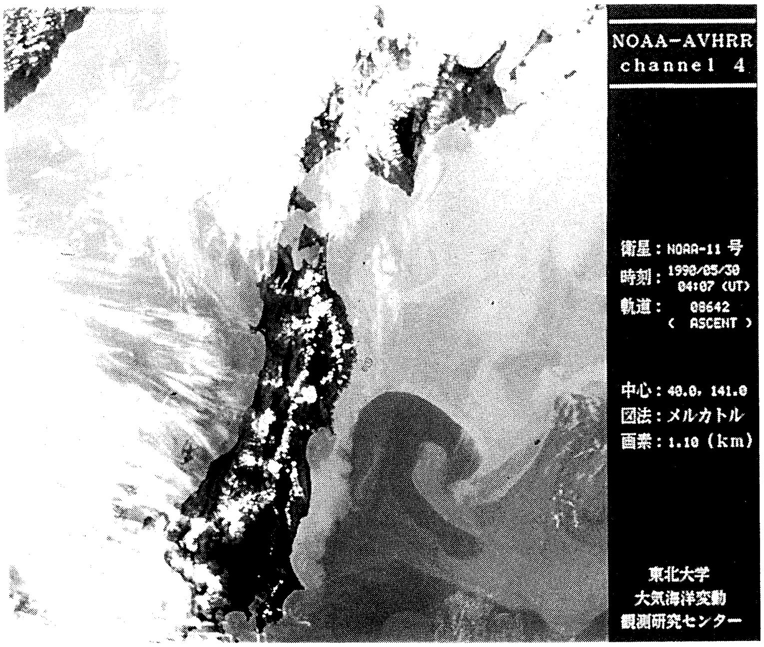

Fig. 2. An image of the warm streamer shot to the warm core ring around St. C22 (*cf.* Fig. 1) from the other ring in the east (NOAA-AVHRR Channel 4)

warm core ring which centered around 38°30′ N, 143°30′ E, and a narrow coastal flow or the Tsugaru Warm Current which flows southward along the isotherms of 12–14°C. Although a warm streamer seems to extrude from the Kuroshio Extension and form a mushroom-shaped warm water body in this figure, satellite imagery (NOAA AVHRR) taken on 30 May indicates that the streamer ran out of the other warm core ring in the east (Fig. 2), which is indicated by a 20°C isotherm on the right end of Fig. 1. The streamer was taken into the southwestern edge (around St. C31) of the warm core ring which occupied the area around Sts. C20–22 (see blow).

Thermal structure in the longitudinal vertical section along Line A illustrates the lens-shaped warm core between 100 m and 400 m depths (Fig. 3). Therefore, we could identify position of the sampling stations in relation to the warm core ring: St. C19 was in south and St. C40 were in north of the ring, Sts. C20 and C22 were at the edge and St. C21 was at the center of the ring. Details of hydrographic structure in the surface layer of these stations, where the plankton samples were collected are given in Figs. 4 and 5. High temperature and high salinity water

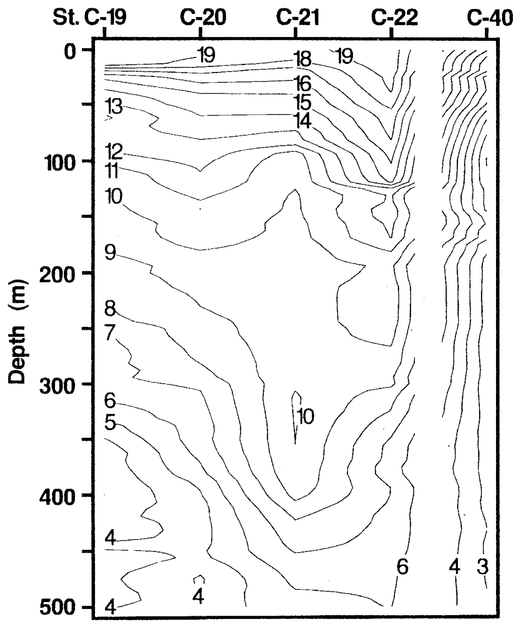

Fig. 3. Distribution of temperature (℃) in vertical section along the longitudinal Line A (143°30′ E) crossing the warm core ring. Data were obtained by CTD casts down to 1000 m. Since Sts. C19–C22 and St. C40 were occupied on different legs of the same cruise, a space is set between Sts. C22 and C40.

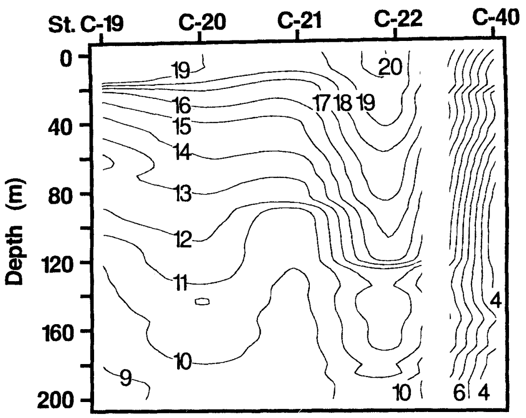

Fig. 4. Detail of temperature (℃) section in 0-200 m layer on Line A. Since Sts. C19–C22 and St. C40 were occupied on different legs of the same cruise, a space is set between Sts. C22 and C40.

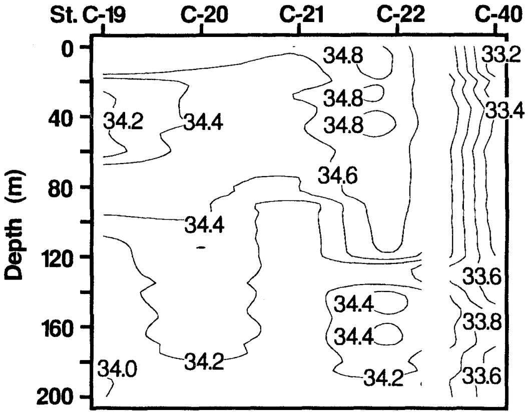

Fig. 5. Salinity (psu) section in 0-200 m layer on Line A. Since Sts. C19–C22 and St. C40 were occupied on different legs of the same cruise, a space is set between Sts. C22 and C40.

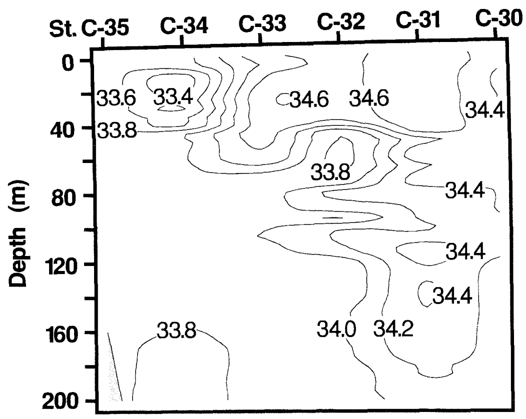

Fig. 6. Temperature(℃) section in 0–200 m layer on Line B crossing western edge of the warm core ring. Data were obtained by CTD casts down to 1000 m.

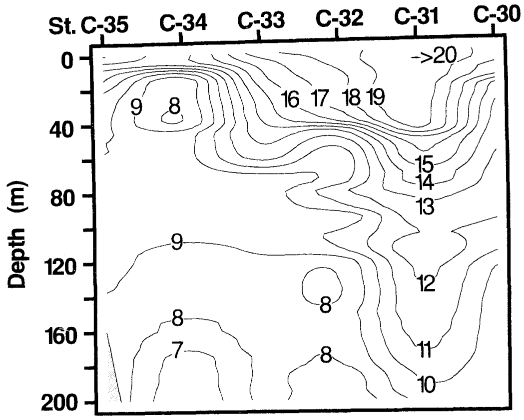

Fig. 7. Salinity (psu) section in 0-200 m layer on Line B.

(>19°C, >34.7 psu) originated from the warm streamer was observed in 0–20 m at Sts. C19 and C20 and in 0–40 m at St. C22. Low salinity subsurface water observed between 20 m and 60 m at St. C19 might be derived from the coastal water off Joban District (*cf.* Fig. 1).

Line B: In the vertical sections of temperature and salinity along Line B (Figs. 6 and 7), low temperature and low salinity coastal water originated from the Tsugaru Warm Current can be seen in the layer between 10 m and 50 m at St. C34, while the same current is illustrated at St. C35 in Fig. 1. In this vertical section, St. C30 was judged to be at the western edge of the ring because edge of the lens-shaped core was detected by the CTD casts (CHIANG, 1993). This is partly illustrated by 10℃ isotherm in Fig.6. St. C31 was judged to be in the warm streamer, which intruded into the surface 40 m at St. C31. Consequently, thermocline and halocline were bent upward to the surface at Sts. C33 and C34 and downward to the subsurface at St. C31.

By the method of T-S analysis described by HANAWA and MITSUDERA (1987), following three water systems were defined. First, high temperature and high salinity water (10–20°C, >34.2 psu) occupied most part of the top 200 m water columns in and south of the warm core ring was recognized as derived from the Kuroshio Current. HANAWA and MITSUDERA (1987) named this type of water the Kuroshio Water System. Second was high temperature and intermediate salinity water (5–20°C, 33.7–34.2 psu) which was observed in west of the ring. This type was named the Tsugaru Warm Current Water System by HANAWA and MITSUDERA (1987). Third was low temperature and low salinity water (0–7°C, 33.0–33.7 psu) named as the Coastal Oyashio Water System (HANAWA and MITSUDERA, 1987). This type was observed in north of the ring (St. C40) indicating the influence of the Oyashio Current. In this paper, however, water types were defined by the principal component analysis using oceanographic data including not only temperature and salinity but also five nutrients (PCA-OD) (Table 1). PC1 explains 47.31% of total variance and positively correlates with dissolved silica and nitrate but negatively with temperature. PC2 accounts for 15.15% of the variance and positively correlates with salinity and nitrite.

In a scatter diagram of PC2 on PC1 eight clusters were identified (Fig. 10), which are given in column OD of Tables 4 and 5. Then, five water types could be recognized (*cf.* Figs. 13 and 14). The first was high temperature surface water (Cluster A) occupied the surface layer in and south of the warm core ring (Sts.C19–C22,C30–C33) as well as in the Kuroshio Extension (St. C18). This is named here the Surface Water Type. The second which occupied the surface layers in west (Sts. C34–C35) and north (St. C40) of the ring is named the Coastal Water Type

Table 1. Oceanographic data used as variables for the PCA-OD and their eigenvectors of PC1 and PC2. Percentage of variance explained is indicated below each of PC1 and PC2.

Variables	PC1 47.31%	PC2 15.15%
Temperature	−0.499	0.242
Salinity	−0.385	0.511
Dissolved Silica	0.450	0.111
Phosphate	0.326	0.023
Nitrate	0.483	0.154
Nitrite	0.182	0.743
Ammonia	0.166	0.302

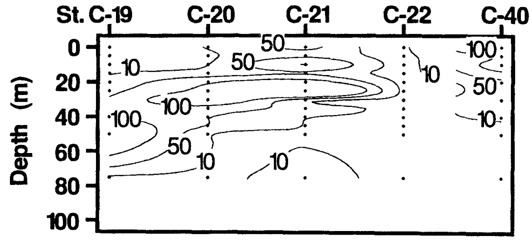

Fig. 8. Distribution in cell number of total diatom populations (10^3 cells l^{-1}) in vertical section along Line A.

(Clusters B and E). This seems to be originated from the northern coastal area off Sanriku District. Similar water type was also found in subsurface at St. C19 (Cluster B), which is likely to be originated from the Joban coastal area instead of the Sanriku coastal area (Fig. 1) and named the Joban Coastal Water Type. The fourth was the Mid-layer Water Type (Clusters C, D and F) widely occupying subsurface layer in almost entire area. The fifth was the Oyashio Water Type (Clusters G and H) which was found in subsurface at Sts. C40 and C59.

3.2. *Diatom Assemblages*

On Line A, the maximum abundance of diatoms in vertical distribution was found in subsurface layer except at St. C40 where the maximum was found at the surface (Fig. 8). It should be noted that the subsurface maximum around 50 m at St. C19 was coincident with position of the Joban Coastal Water Type described

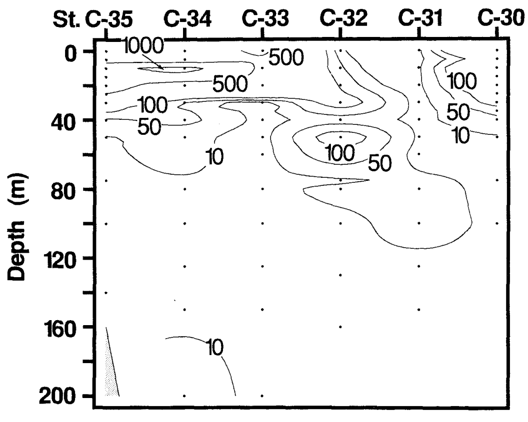

Fig. 9. Distribution in cell number of total diatom populations (10^3 cells l^{-1}) in vertical section along Line B.

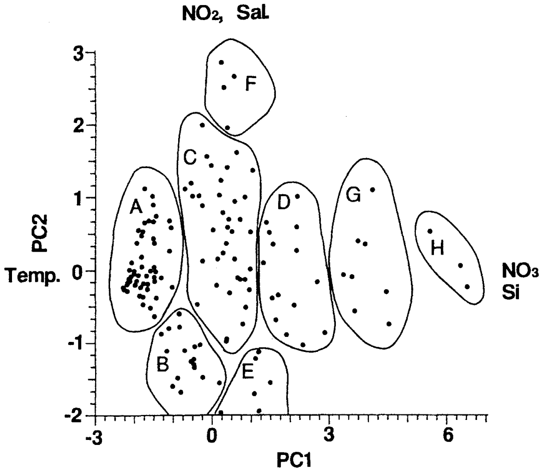

Fig. 10. Scatter diagram of PC2 on PC1 of the principal component analysis using oceanographic data (PCA-OD) (*cf.* Table 1). Envelops denote eight clusters identified by an average cluster analysis.

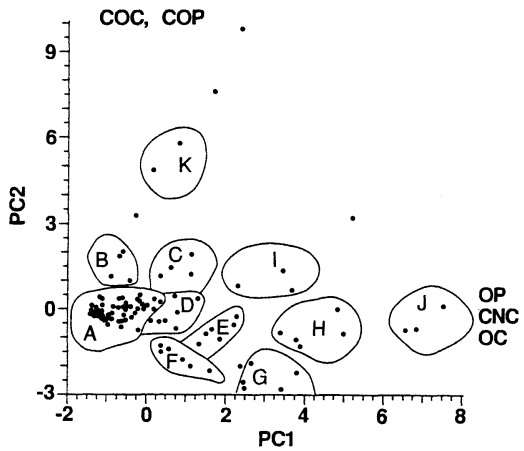

Fig. 11. Scatter diagram based on 14 groups of diatoms which were grouped by their distributional characteristics (PCA-DC) (*cf.* Table 2). Envelops denote 11 clusters identified by cluster analysis. Five points out of envelops A-K are marked # in Tables 5 and 6.

above. On the other hand, abundance of diatoms was low at St. C22 and in the warm streamer in the surface layer shallower than 20 m at Sts. C19–C20.

On Line B, the maximum abundance was generally found in the top 20 m except Sts. C31 and C32, where diatom became abundant in 50–100 m layer (Fig. 9). In the surface layer at St. C31 occupied by the warm streamer, diatom stock was low as observed at Sts. C19 and C20.

In the principal component analysis based on groups of diatom species classified by the distri-

Table 2. Fourteen types of diatoms grouped by their distributional characteristics used as variables for the PCA-DC and their eigenvectors of PC1 and PC2. Percentage of variance explained is indicated below each of PC1 and PC2.

Diatom group/Variable	PC1 28.43%	PC2 18.04%
Cold oceanic centric diatoms (COC)	0.074	0.572
Cold neritic centric diatoms (CNC)	0.452	0.158
Warm oceanic centric diatoms (WOC)	0.306	−0.235
Warm neritic centric diatoms (WNC)	0.154	0.311
Oceanic cosmopolitan centric diatoms (OCC)	0.268	−0.267
Neritic cosmopolitan centric diatoms (NCC)	0.321	0.035
Other centric diatoms (OC)	0.430	−0.057
Cold oceanic pennate diatoms (COP)	0.040	0.570
Cold neritic pennate diatoms (CNP)	0.000	0.000
Warm oceanic pennate diatoms (WOP)	0.057	−0.076
Warm neritic pennate diatoms (WNP)	0.249	−0.266
Oceanic cosmopolitan pennate diatoms (OCP)	0.000	0.000
Neritic cosmopolitan pennate diatoms (NCP)	0.193	0.127
Other pennate diatoms (OP)	0.457	0.042

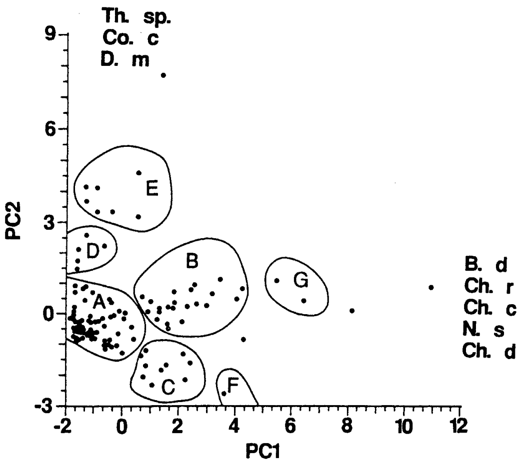

Fig. 12. Scatter diagram based on 13 dominant and common daitom species which occurred in more than 50 % of samples (PCA-DS) (*cf.* Table 3). Envelops denote seven clusters identified by cluster analysis. Six points out of envelops A-K are marked # in Tables 5 and 6, two of which are far out of this diagram.

bution nature (PCA-DC), the first (PC1) and second principal components (PC2) account for 46.47% of total variance (Table 2). PC1 positively correlates with three groups of cold neritic centric diatoms, other centric diatoms and other pennate diatoms, and PC2 with two groups of cold oceanic centric diatoms and cold oceanic pennate diatoms. In principal component analysis based on dominant diatom species (PCA-DS), PC1 and PC2 account for 36.16% of the variance. PC1 is influenced by *Bacteriastrum delicatulum, Chaetoceros compressum, C. didymum, C. radicans* and *Nitzschia seriata*, and PC2 by *Corethron criophilum, Denticulopsis marina* and *Thalassiosira* sp. (Table 3). Figs. 11 and 12 illustrate scatters of PC2s on PC1s in PCA-DC and PCA-DS, respectively, and eleven and seven clusters were identified. These results are summarized in the columns of DC and DS in Tables 4 and 5. Compiling these results nine diatom assemblages were finally defined as below (also *cf.* Table 6).

(1) Kuroshio Extension Assemblage: This assemblage was defined by the combinations of Cluster A in PCA-DC and Cluster C or Cluster F in PCA-DS. These combinations can be expressed in A-C and A-F and found only in the surface

Table 3. Twenty-four dominant diatom species, which occurred in more than 50% of samples, used as variables for the PCA-DS and their eigenvectors of PC1 and PC2. Percentage of variance explained is indicated below each of PC1 and PC2.

Variables	PC1 23.00%	PC2 13.16%
Asterionella glacialis	0.191	−0.070
Bacteriastrum delicatulum	0.377	−0.022
Chaetoceros compressum	0.326	0.045
Chaetoceros decipiens	0.134	0.014
Chaetoceros didymum	0.323	−0.101
Chaetoceros peruvianum	0.160	0.069
Chaetoceros radicans	0.330	0.157
Corethron criophilum	0.031	0.481
Denticulopsis marina	−0.017	0.470
Leptocylindrus danicus	0.070	−0.125
Navicula distans	0.134	0.056
Navicula membranacea	0.170	−0.082
Navicula sp.	−0.022	−0.041
Nitzschia closterium	0.232	0.096
Nitzschia longissima	0.277	0.008
Nitzschia seriata	0.324	−0.057
Nitzschia sp.	−0.001	0.361
Rhizosolenia alata	0.191	0.108
Rhizosolenia bergonii	0.124	−0.154
Rhizosolenia fragilissima	0.247	−0.004
Rhizosolenia stolterfothii	0.154	−0.187
Pseudoeunotia doliolus	0.124	0.031
Thalassionema nitzschioides	0.119	−0.144
Thalassiosira sp.	0.042	0.488

layer between 0 m and 35 m at St. C18 (Table 4). Dominant species in this assemblage were *C. compressum, Hemiaulus sinensis, Leptocylindrus danicus, N. seriata* and *Thalassionema nitzschioides*, which have been reported as warm neritic or neritic cosmopolitan species. Population density of this assemblage ($3\times10^4-1.2\times10^5$ cells l^{-1}) was not large comparing to the other assemblages in this season.

(2) Joban Coastal Assemblage: This assemblage was defined by Clusters D, E, F, G, H in PCA-DC, all of which appeared in the fourth quadrant of scatter diagram (Fig. 11), and Clusters B and G in PCA-DS (Tables 4 and 5). Isolated Cluster # in PCA-DS found at 10 m at St. C21, which is different from Clusters B and

G but very similar to them, appeared in the first quadrant of Fig. 12. Therefore, this cluster was also categorized in this assemblage. This assemblage was found in the subsurface layer (20–50 m) at St. C19 below the warm streamer and in the surface and subsurface layer of the warm core ring, *i.e.* 20–45 m St. C20, 0–35 m at St. C21 and 0–35 m at St. C30. Dominant species were *Chaetoceros compressum, C. peruvianum, C. radicans, N. seriata* and *Pseudoeunotia doliolus*. Peak-forming species, whose peak (or one of peaks) in distribution occurred in the distributional range of this assemblage, were *C. compressum, C. peruvianum, C. radicans, P. doliolus, B. delicaturum* and *Rhizosolenia fragilissima*. These species indicate the relatively warm water preference of this assemblage, while a few cold neritic species were mixed with. Population density was intermediate being $4\times10^4-4.8\times10^5$ cells l^{-1}.

(3) Coastal Front Assemblage: This assemblage was clearly defined by combinations of clusters of G-# and H-# and also by D-B, E-E and F-A. The latter three were considered to be derived from A-A and similar to H-# in the scatter diagrams. This assemblage was intermediate in population density ($1\times10^5-6\times10^5$ cells l^{-1}) and found only in frontal zone between the warm core ring and the coastal water (Sts. C32 and C33) (Table 5). Dominant species were *B. delicatulum, C. compressum, C. peruvianum, C. radicans* and *N. seriata*, and the peak-forming species were *Asterionella gracialis, B. delicatulum, C. compressum, C. didymum, C. peruvianum* and *P. doliolus*. This species composition seems to be similar to the Joban Coastal Assemblage, but the neritic nature is much stronger.

(4) Tsugaru Warm Current Assemblage: This assemblage was defined by Cluster I and its closely allied Cluster # in PCA-DC and by Clusters B, C and F in PCA-DS. This assemblage was found in 5–20 m at St. C34 where the Tsugaru Warm Current flowed from north. The maximum diatom abundance throughout this investigation was observed in this assemblage (10 m at St. C34). The dominant species were *C. compressum, C. frichei, C. radicans, L. danicus* and *N. seriata*, and the peak-forming species were *C. frichei, R. fragilissima, R. stolterfothii, Skeletonema costatum* and *T. nitzschioides*. These species indicate the neritic nature of this assemblage. Population density was $2\times10^5-1.1\times10^6$ cells l^{-1}.

(5) Southern Sanriku Coastal Assemblage: The assemblage defined by C-C was found in 0–25 m at St. C35 which was the nearest station to the coast. However, neritic nature as well as population density ($3\times10^5-9\times10^5$ cells l^{-1}) of this assemblage was smaller than those of the Tsugaru Warm Current Assemblage. The dominant species were *C. compressum, C. curvisetum, C. frichei, L. danicus* and *N. seriata*, and the peak-forming species were *C. curvisetum, C. decipiens* and *L. danicus*.

(6) Northern Mixed Assemblage 1: The assemblage defined by D-B and I-B occurred in 0-10 m at St. C40 which was located in north of the warm core ring. The dominant species were *C. curvisetum, C. radicans, L. danicus, N. closterium* and *N. seriata*, and the peak-forming species were *A. gracialis, B. delicatulum, C. compressum, C. curvisetum, C. decipiens, C. frichei, C. radicans, L. danicus* and *T. nitzschioides*. This species composition indicates that this assemblage was formed by mixing of cold-water species such as *C. decipiens* into the Background Assemblage, which is described later. Population density was intermediate, being $1.1\times10^5-3\times10^5$ cells l^{-1}.

(7) Northern Mixed Assemblage 2: This assemblage defined by A-D and A-E occurred in 20-40 m at St. C40 or just below the Northern Mixed Assemblage 1. Therefore, population density was one order of magnitude lower than the Assemblage 1, being $1.2\times10^4-4\times10^4$ cells l^{-1}. The dominant species were *C. curvisetum, D. marina, L. danicus, N. closterium* and *N. seriata*. The peak-forming species was not found in this assemblage.

(8) Oyashio Assemblage: This assemblage was defined by combinations of Clusters #, K and B in PCA-DC and of Cluster #, D and E in PCA-DS. This was found at 0–50 m and 100–150 m at St. C59 and dominated by *Chaetoceros concavicorne, C. curvisetum, C. radicans, D. marina* and *Thalassiosira nordenskioldii*. Since St. C59 was isolated in north of the Polar Frontal Zone, the peak-forming species were not judged. Nevertheless, cold-water nature of this

Table 4. Distribution of the clusters separated by three PCAs based on oceanographic data (OD), and abundances of distributional groups (DC) and dominant species (DS) as variables for Leg 1 of the Cruise KT-90-7.

ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS
C18-0	A	A	C	C19-0	A	A	A	C20-0	A	A	A	C21-0	A	D	B	C22-0	A	A	A	C40-0	E	I	B
5	A	A	C	5	A	A	A	5	A	A	A	5	A	D	B	5	A	A	A	5	B	D	B
10	A	A	C	10	A	A	A	10	A	A	A	10	A	E	#	10	A	A	A	10	B	D	B
15	A	A	F	15	A	A	A	15	A	A	A	15	A	D	B	15	*	A	A	20	E	A	D
20	A	A	C	20	B	F	A	20	A	E	B	20	C	E	B	20	A	A	A	30	D	A	E
25	A	A	F	25	B	F	A	25	*	E	B	25	A	H	B	25	A	A	A	40	G	A	D
30	A	A	C	35	C	*	*	30	A	G	B	30	C	F	A	30	A	A	A	50	E	A	A
35	A	A	C	40	B	G	B	35	*	G	B	35	F	D	A	35	A	A	A	75	D	A	A
40	A	A	A	50	B	H	B	40	C	F	A	40	F	A	A	40	A	A	A	100	G	A	A
45	A	A	A	75	C	A	A	45	F	F	A	45	C	A	A	45	A	A	A	125	D	A	A
50	A	A	A					50	F	A	A	50	C	A	A	50	A	A	A	150	G	A	A
								75	F	A	A	75	C	A	D	75	A	A	A	200	G	A	A

*: Samples were not collected from the layers.
#: The community is different from all others.

Table 5. The same as Table 4 but for Leg 2.

ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS	ST& Dep.	OD	DC	DS
C30-0	A	J	G	C31-0	A	A	A	C32-0	A	A	A	C33-0	A	J	#	C34-0	B	A	A	C35-0	B	C	C	C59-0	E	#	E
5	A	E	B	10	A	A	A	10	A	A	A	10	A	J	#	5	B	I	C	5	B	A	A	5	E	*	*
10	A	H	G	20	A	A	A	20	A	A	A	20	C	H	#	10	B	#	F	10	B	C	C	10	E	#	E
15	C	H	B	30	A	A	A	30	A	D	B	30	C	A	A	20	B	I	B	15	B	C	A	15	E	K	#
20	C	G	B	40	A	A	A	40	C	A	A	40	C	A	A	30	D	A	A	20	B	C	C	20	G	#	E
25	D	G	B	50	B	A	A	50	C	E	E	50	C	A	A	40	C	A	A	25	B	B	A	30	D	K	#
30	C	G	B	60	C	A	A	75	D	F	A	60	C	A	A	50	C	A	A	30	B	A	A	40	G	B	E
35	C	F	A	80	C	A	A	80	C	A	A	80	C	A	A	80	B	A	A	40	B	A	A	50	G	B	E
40	C	A	A	100	C	A	A	100	D	A	A	100	C	A	A	100	C	A	A	50	C	A	A	75	G	A	A
50	C	A	A	125	C	A	A	130	D	A	A	125	C	A	A	125	C	A	A	75	C	A	A	100	H	A	D
75	C	A	A	150	D	A	A	160	D	A	A	150	C	A	A	150	C	A	A	100	C	A	A	150	H	B	D
100	B	A	A	200	D	*	*	200	D	A	A	200	D	A	A	200	D	A	A	140	C	A	A	200	H	A	A

*: Samples were not collected from the layers.
#: The community is different from all others.

assemblage is clearly indicated by these dominant species, while a few warm neritic species were mixed. Population density was intermediate being $2\times10^4-8\times10^5$ cells l^{-1}.

(9) Background Assemblage: This assemblage was defined by A-A. Neritic cosmopolitans *C. compressum*, *N. closterium*, *S. seriata*, *T. nitzschioides*, and a cold neritic *C. radicans* were major components of this assemblage. Important is that this assemblage was smallest in population density but most widely distributed over the sampling area. The density rarely exceeded 1×10^4 cells l^{-1} with a few exceptions in the surface layer at St. C34. This assemblage is considered to be produced and distributed homogeneously in water column by winter convection

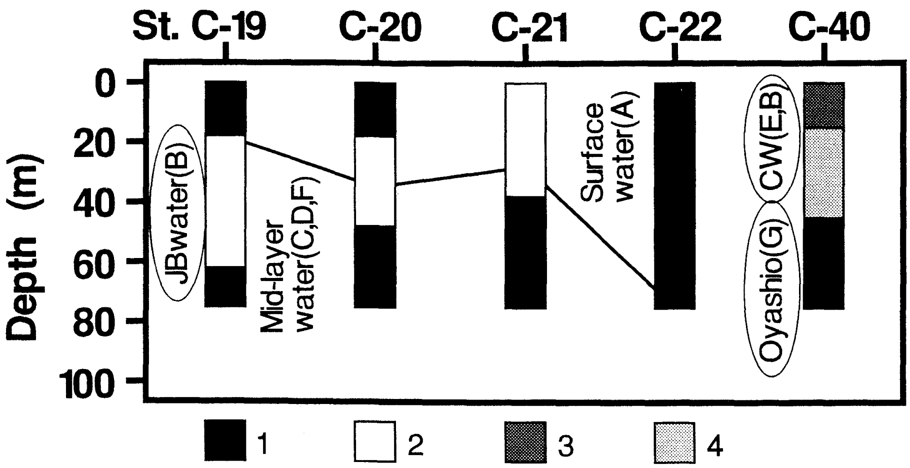

Fig. 13. Distributions of water types and diatom assemblages defined by PCAs in vertical section along Line A (*cf.* Table 6). 1: Background Assemblage, 2: Joban Coastal Assemblage, 3: Northern Mixed Assemblage 1, 4: Northern Mixed Assemblage 2.

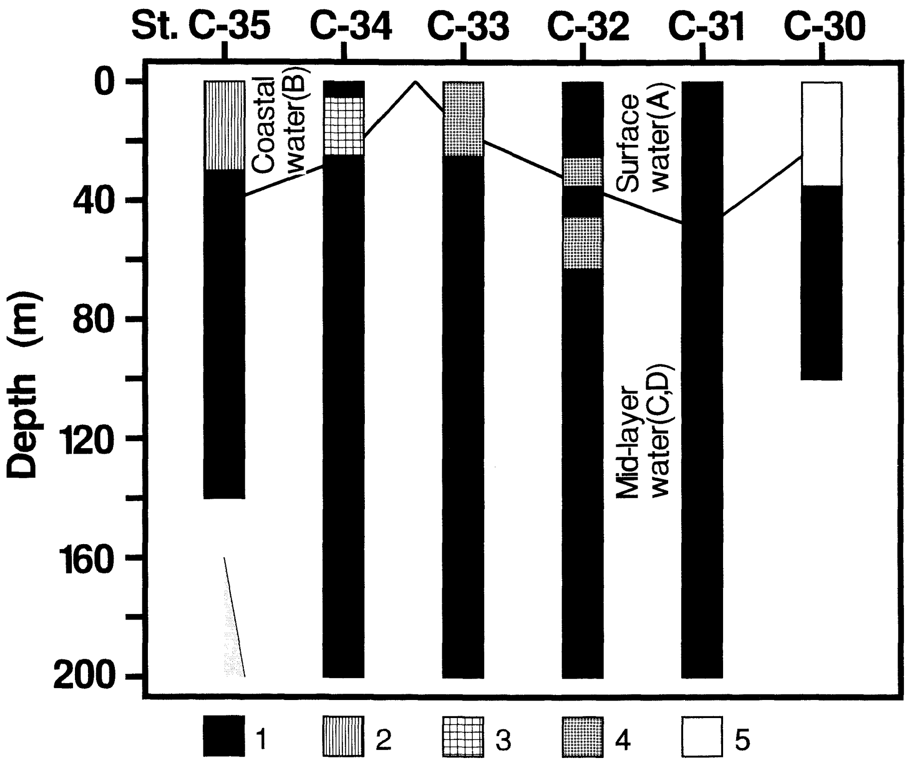

Fig. 14. Distributions of water types and diatom assemblages defined by PCAs in vertical section along Line B (*cf.* Table 6). 1: Background Assemblage, 2: Southern Sanriku Coastal Assemblage, 3: Tsugaru Warm Current Assemblage, 4: Coastal Front Assemblage, 5: Joban Coastal Assemblage

down to the permanent halocline in the entire Polar Frontal Zone (CHIANG and TANIGUCHI, 1993).

4. Discussion

PCA-OD yielded double layered structure of water column in vertical sections along Lines A and B where the shallow Surface Water Type covers the thick Mid-layer Water Type except the southernmost (St. C19) and northernmost stations (St. C40) outside of the warm core ring. At the latter two stations the Joban Coastal Water Type, the Coastal Water Type and the Oyashio Water Type were identified separately from the prevailing two water types in the surface and mid-layers. This result gives rather simple picture of hydrographic feature in this area as if foreign water masses other than the Surface and Mid-layer Water Types intrude only at both edges of Line A (Sts. C19 and C40) (Figs. 13 and 14).

Distribution of the nine diatom assemblages defined above indicates configuration of water types of different natures much more precisely. The Kuroshio Extension Assemblage which was composed of warm neritic species existed only in the top 35 m at St. C18. This indicates that the Kuroshio Extension water carrying neritic species entrained by the Kuroshio during its flow along southeast coast of western to central Japan (YAMAMOTO *et al.*, 1988) did not extend to the other stations. Although the warm streamer is illustrated as if ran out from the Kuroshio Extension in Fig. 1, no direct influence of the Extension water was observed in the diatom assemblages at the surface at Sts. C19, C20, C31 and C32 in and near the streamer.

At the latter stations the Background Assemblage was found, below which the Joban Coastal Assemblage containing a few cold neritic species was found (Figs. 13 and 14). Coexistence of the cold neritic species indicates that the Joban Coastal Assemblage came from the Joban coastal region north of the Kuroshio Extension. The Joban Coastal Assemblage was found as intruded subsurface layer (20–70 m) at St. C19 and uplifted to the surface at Sts. C21 and C30. Low-salinity water (<34.5 psu) found at Sts. C19 and C21 seems to indicate partly this course (Fig. 5) but PCA-OD as well as conventional T-S analysis could not reveal this. Such a discrepancy is thought to be produced by different natures between the physico-chemical property of water and the plankton assemblage. The former (temperature, salinity and five nutrients) changes gradually and continuously by mixing of water types. However, individual plankters continue to exist after their populations are mixed. This conservative nature vests plankton assemblage with practical value as the tracer of changing and mixing water types (FRYXELL *et al.*, 1984; KACZMARSKA *et al.*, 1986). PCAs can identify those assemblage different from neighboring assemblages being composed of similar species.

At St. C59 in the northern extreme of the study area the Oyashio Assemblage was found. Since this assemblage contained a few warm water species, it can be understood that influence of the warm water had extended to east of Hokkaido in this season. The Oyashio Assemblage was likely to be modified into the Northern Mixed Assemblages 1 and 2 by further mixing with warm water at St. C40, which indicated by relative position of respective clusters in Figs. 11 and 12. Degree of the mixing of warm water was lesser in subsurface (Assemblage 2) than in the surface (Assemblage 1) as expected. On the other hand, typical Oyashio Assemblage was not found even below the Assemblage 2 where the Oyashio Water System was identified by T-S analysis; the Background Assemblage was found there. This fact demonstrates that the Background Assemblage which had been formed in winter through entire water column in the Oyashio and the mixed water regions (CHIANG and TANIGUCHI, 1993) was kept unchanged below the euphotic zone. This is the possible reason why the Background Assemblage was pervading the deeper part of water columns over the entire area (Figs. 13 and 14).

In the Coastal Water Type at Sts. C34 and C35 which was identified by PCA-OD, two different diatom assemblages, *i.e.* the Tsugaru Warm Current Assemblage and Southern Sanriku Coastal Assemblage, were found. The Tsugaru Warm Current is known as a narrow coastal flow in the surface layer which is hardly distinguished from the Sanriku coastal water system by conventional T-S analysis (*cf.* KAWAI, 1972; HA-

NAWA and MITSUDERA, 1987). The present PCA-OD could not distinguish these two waters too, but the PCA-DC and PCA-DS detect the distinction between them. Revelation of the Coastal Front Assemblage at Sts. C32 and C33 is an another example showing high ability of diatom assemblage to distinguish slightly different water types. Two-layered structure of this assemblage at St. C32 (Fig. 14) strongly indicates the complexity in fine scale of local mixing process of converging waters at frontal region.

The facts described above demonstrate that the distribution pattern of diatom assemblages was not always consistent with that of the water types, usually being more complex. The Background Assemblage pervaded the entire section, on which seven other assemblages were distributed in different way from the distribution of water types (Figs. 13 and 14). In other words, PCA-DC and PCA-DS can trace distribution of different waters more precisely than PCA-OD and conventional T-S analysis as well.

It should be noted again that the Background Assemblage was smallest in population density among assemblage found in this season except the Nothern Mixed Assemblage 2 which was at the same level or exceeded very slightly the Background Assemblage in the density. Since the Northern Mixed Assemblage 2 occurred in subsurface layer at St. C40, low underwater light intensity may be primarily responsible for its lower population density. The same can undoubtedly be the case for the Background Assemblage distributed in subsurface layer over entire area. However, although the Background Assemblage was also found commonly in the surface layer (Figs. 13 and 14), its size was small. This is most likely to indicate that the diatom production is not high in the background water type occupying large part of the North Pacific Polar Front (*cf.* TANIGUCHI, 1981). The production is enhanced in the surface layer where the other water types such as warm streamer and coastal water as well as the Oyashio water intrude, where, in turn, new assemblage are formed.

Acknowledgment

We are grateful to Drs. A. OKATA, K. MORI and Y. ENDO of the Tohoku University for their constructive comments on this work. Kind guidance in PCA given by Dr. Y. ENDO was particularly appreciated. We also thank Dr. H. KAWAMURA of the same university for his kind permission for us to use satellite imagery filed in the Center for Atmospheric and Oceanic Science.

Reference

CHIANG, K.P. (1993): Studies on Oceanographic Structure and Distribution of Phytoplankton Assemblages in the Sea Area off Eastern Hokkaido and Tohoku Districts, Japan. Ph. D. Thesis, Tohoku University, Sendai, 260 pp. (In Japanese with English abstract)

CHIANG, K.P. and A. TANIGUCHI (1993): Formation of diatom assemblage distributed widely in the North Pacific Polar Frontal Zone. Bull. Jap. Soc. Fish. Oceanogr., **57**, 307–318.

FRYXELL, G.A., R.W. GOULD, Jr., E.R. BALMORI and E.C. THERIOT (1985): Gulf Stream warm core rings: phytoplankton in two fall rings of different ages. J. Plankton Res., **7**, 339–364.

HANAWA, K. and H. MITSUDERA (1987): Variation of water system distribution in the Sanriku coastal area. J. Oceanogr. Soc. Japan, **42**, 435–446.

JAPAN FISHERIES INFORMATION SERVICE CENTER (1990): Prompt Report of Fisheries Oceanographical Conditions, No. 1119, 2 pp. (In Japanese)

KACZMARSKA, I., G.A. FRYXELL and T.P. WATKINS (1986): Effect of two Gulf Stream warm-core rings on distribution patterns of the diatom genus *Nitzschia*. Deep-Sea Res., **33**, 1843–1868.

KAWAI, H. (1972): Hydrography of the Kuroshio and Oyashio, pp. 129–309. *In* Kaiyo-kagaku Kiso Koza, 2 MASUZAWA, J. (ed.) Tokai Univ. Press., Tokyo (in Japanese).

KAWAI, H. and S. SAITOH (1986): Secondary fronts, warm tongues and warm streamers of the Kuroshio Extension system. Deep-Sea Res., **33**, 1487–1507.

KOKUBO, S. (1960): Planktonic Diatoms. Koseisha Koseikaku, Tokyo, 330 pp. (in Japanese).

MARUMO, R. (1967): General features of diatom communities in the North Pacific in summer. Inform. Bull. Planktol. Japan, Commem. No. Dr. Y. MATSUE, 115–122.

MARUMO, R. and M. AMANO (1956):Planktological and hydrographical conditions in the Yakumizu water east of Miyako in May 1955. J. Oceanogr. Soc. Japan, **12**, 53–58. (in Japanese with English abstract)

MARUMO, R., H. TAKANO and Y. KAWARADA (1966): Illustrations of the Marine Plankton of Japan, Vol. 1. Soyoshya, Tokyo, 69 pp. (in Japanese).

NAGATA, Y., K. OHTANI and M. KASHIWAI (1992): Subarctic Gyre in the North Pacific Ocean. Umi no Kenkyu, **1**, 75–103. (in Japanese with English abstract)

PIELOU, E.C. (1984): The Interpretation of Ecological Data. John Wiley, New York, 263 pp.

TANIGUCHI, A. (1981): Plankton productivities in the Pacific Subarctic Boundary Zone: food condition of the pelagic fishes. Res. Inst. Nor. Pac. Fish. Hokkaido Univ., Spec. Vol., 23–35. (in Japanese with English abstract)

YAMAJI, I. (1984): Illustration of the Marine Plankton of Japan (3rd edn.), Hoikusha, Osaka, 537 pp. (in Japanese)

YAMAMOTO, T., A. TANIGUCHI and S. NISHIZAWA (1981): Microplankton distribution at an oceanic front formed in the Sanriku Water off northeast Japan. Bull. Plankton Soc. Japan, **28**, 111–120.

YAMAMOTO, T., S. NISHIZAWA and A. TANIGUCHI (1988): Formation and retention mechanisms of phytoplankton peak abundance in the Kuroshio Front. J. Plankton Res., **10**, 1113–1130.

北太平洋極前線海域の暖水塊および その周辺における珪藻群集の分布

蔣 国平・谷口 旭・加藤 聡

要旨：北太平洋極前線海域における晩春の珪藻群集の分布を，水型の分布との関連で調査した。主成分分析法により，珪藻は９群集，また水型は５水型に分けられた。両者の分布は常に一致するとは限らなかったが，それは海水の物理化学的性格よりも珪藻群集の方が保存的なためであると考えられる。この海域の背景をなすように最も広く分布する群集を背景群集と名付けたが，その主要構成種は沿岸性コスモポリタン種であり，群集密度は低かった。広く背景をなす極前線の混合水の表層に異水型が流入したときに，珪藻群集の生産が促進され，異なった種組成の珪藻群集が新しく形成されるらしいことがわかった。