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New Planktic Foraminiferal Transfer Functions for the Kuroshio-Oyashio Current Region off Japan

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Abstract. Factor analysis of planktic foraminiferal assemblages analyzed in sediment samples from the Northwest Pacific Ocean near Japan defines five major factors including the Kuroshio, Transitional Water, Oyashio, Kuroshio Gyre Margin and Coastal Water factors which, when mapped, show distinctive distributions. These factors account for over 94% of the total variance. Each of the factors can be treated as an independent variable in a regression analysis. Equations relating factors to winter and summer sea-surface temperatures (SSTs) show a high degree of accuracy. The standard errors of estimate for the transfer function equations PFJ-125 established in this study average about ±1.75°C for estimated winter temperatures, and about ±1.17°C for summer temperatures.

Transfer functions PFJ-125 were applied to assemblages representing the last 12 K yrs. in piston core C-1 collected in the area off Joban, northeast Honshu, Japan. The lowest estimated winter SST is 4.1°C and 18.5°C for the summer SST at 10,500 yrs. B.P. whereas at 6,300 yrs. B.P. the winter highest SST is 12.8°C and 23.9°C in the summer. Based on down-core variations in estimated winter and summer SST and fluctuations of the five identified factor loadings, the C-1 core site was alternatively under the influence of the Oyashio and Kuroshio Fronts through the last 12 K yrs. Marine conditions at core site C-1 at 10,500 yrs. B.P. are comparable with those recorded in the same area for the last glacial maximum.

Key words: Latest Quaternary, paleoenvironments, planktic foraminifera, Q-mode factor analysis, transfer functions

Introduction

Planktic foraminifera (unicellular shelled protozoans) live in surface and near-surface ocean water and their distribution generally corresponds to the world's climatic zones and oceanic surface water masses (Bé and Tolderlund, 1971; Bradshaw, 1959). The composition of planktic foraminiferal assemblages accumulated in surface sediments on the ocean bottom reflects oceanographic conditions of the overlying surface water (Belyayeva, 1969; Bé, 1977).

Past variations in sea surface temperature can be estimated through quantitative analysis of fossil planktic foraminiferal assemblages in deep sea sediments. The transfer function introduced by Imbrie and Kipp (1971) is derived simply from spatial correlations between modern oceanographic data (water temperature, salinity, etc.) and census data for surface sediment collected from sea bottom assemblages of planktic foraminifera. These authors carried out factor analysis of planktic foraminiferal assemblages from surface sediments as variables, obtained statistically derived varimax assemblages which have high correlations with environmental factors, and subsequently calculated the transfer function and estimated sea surface temperatures (SSTs) by regression analysis. This method is now widely applied in Quaternary research as the technique provides calibrated quantitative estimates of several parameters of past oceanic environments including surface temperatures (see for example CLIMAP, 1976; Moore *et al.*, 1980, and others).

This method has been used by many investigators to obtain the transfer function for planktic foraminiferal assemblages in the north and equatorial Atlantic (Gardner and Hays, 1976; Kipp, 1976; Prell *et al.*, 1976; Dowsett and Poore, 1990 and others). These latter functions, however, have inherent geographic limits in their applicability because they are entirely based upon biotic and oceanographic parameters defined for a given geographically confined oceanic region. In order to interpret paleoenvironmental changes as accurately as possible, it is necessary to select a transfer function specific to the region in question. This method was applied to planktic foraminifers in the western Pacific Ocean by Thompson (1981), Oda *et al.* (1983) and Takayanagi *et al.* (1987).

In the northwestern Pacific Ocean near Japan, there are two dominant surface currents, the north flowing Kuroshio and the south-flowing Oyashio. Surface sediments used by Thompson (1981) to derive the transfer function FP-12E were mainly collected in the Kuroshio Region, with only a few samples from the Oyashio Region near Japan. The Oda *et al.* (1983) and Takayanagi *et al.* (1987) studies lacked samples from the Kuroshio Region. Therefore, the transfer function equations derived by their authors are not efficient enough to apply to cores from areas near Japan under the influence of the Oyashio and Kuroshio Currents.

In this study, we have attempted to formulate new multiple regression equations applicable to the Kuroshio to Oyashio regions and derive transfer functions to estimate sea-surface temperature (SST) in the piston core KT81-19, C-1 taken along the Joban coast off Northeast Honshu, Japan (Figure 1).

Hydrographic conditions of the Northwest Pacific Ocean near Japan

The Japanese Islands extend in an arc from northwest to southeast along the northwestern margin of the Pacific Ocean. The surface ocean off Japan can be generally subdivided into three regions which correspond to distinctive surface flow patterns and physical properties (Kawai, 1972) including the Kuroshio Area, the Oyashio Area and the Perturbed (Transitional) Area (Figure 1). The hydrography in each area is summarized as follows.

The Kuroshio Current represents one of the major western boundary currents in the world ocean and flows toward the northeast along the coast of Japan. The so-called Kuroshio extension, which runs eastward away from Japan into the Pacific, is distinguished from the Kuroshio Current proper which runs along the coast. The Kuroshio area of influence extends from seas off southwest Japan to approximately Lat. 35°N, where the northern boundary is determined by the Kuroshio Front and the Kuroshio Extension.

Two stable flow patterns are known for the Kuroshio Current (Taft, 1972; Nitani, 1975). One runs parallel to the Japanese Islands and bathes the upper portion of the continental slope. Another is called the meander, which leaves the continental slope off the Enshu Gulf (Enshu-nada, Lat. 33°N). The meander surrounds the Cold Water Mass resulting from upwelling of cold water (Nan'niti, 1958, 1960), leading to sea surface temperatures some 4 to 5°C lower than mean surrounding values (Fujimori, 1964). Although many investigators have suggested that the meander must be treated within the context of the Pacific circulation as a whole (Shoji, 1972), there are not enough data at this time to fully analyze the meander and associated occurrence of the Cold Water Mass.

The Oyashio Current is the second most important surface current near Japan; it flows southward along the southeast coast of Hokkaido and is characterized by low temperature and low salinity (Kawai, 1972). The Oyashio area of influence is located north of approximately Lat. 41°N. The southern boundary of this area is demarcated by the Oyashio-Kuroshio Front which lies approximately at Lat. 38°N as a weak easterly flow of the Oyashio, and also a southward intrusion of the Oyashio, termed the first Oyashio Intrusion.

The so-called Perturbed Area is located between approximately Lat. 38°N to 41°N between the Oyashio and Kuroshio Fronts and the axis of the Kuroshio Extension, where steep temperature and salinity gradients prevail. Numerous eddies exist in the Perturbed Area forming an area of a complicated surface character (Kawai, 1972).

Finally, a warm surface current flows from the Sea of Japan into the northwest Pacific through the Tsugaru Strait (the so-called Tsugaru Current) and affects the surface water from the Tsugaru Strait to off Kinkazan Island (Kawai, 1972; Moriyasu, 1972) at approximately Lat. 38°N. The Tsugaru Warm Current has its origin in the Tsushima Current, a warm current which flows northward into the Sea of Japan through the Tsushima Strait.

Sea surface temperature (SST) data used in this report are based on the Marine Environmental Atlas compiled by the Japan Oceanographic Data Center (1978) (Figure 2). In the Kuroshio Area, SST ranges from 20°C to 30°C in the summer, and 7.5°C to 20°C in the winter. In the Oyashio Area, SST ranges from 14°C to 22°C in the summer, and −2.5°C to 10°C in the winter. In the Perturbed Area, SST ranges from 18°C to 22°C in the summer, and 5°C to 10°C in the winter.

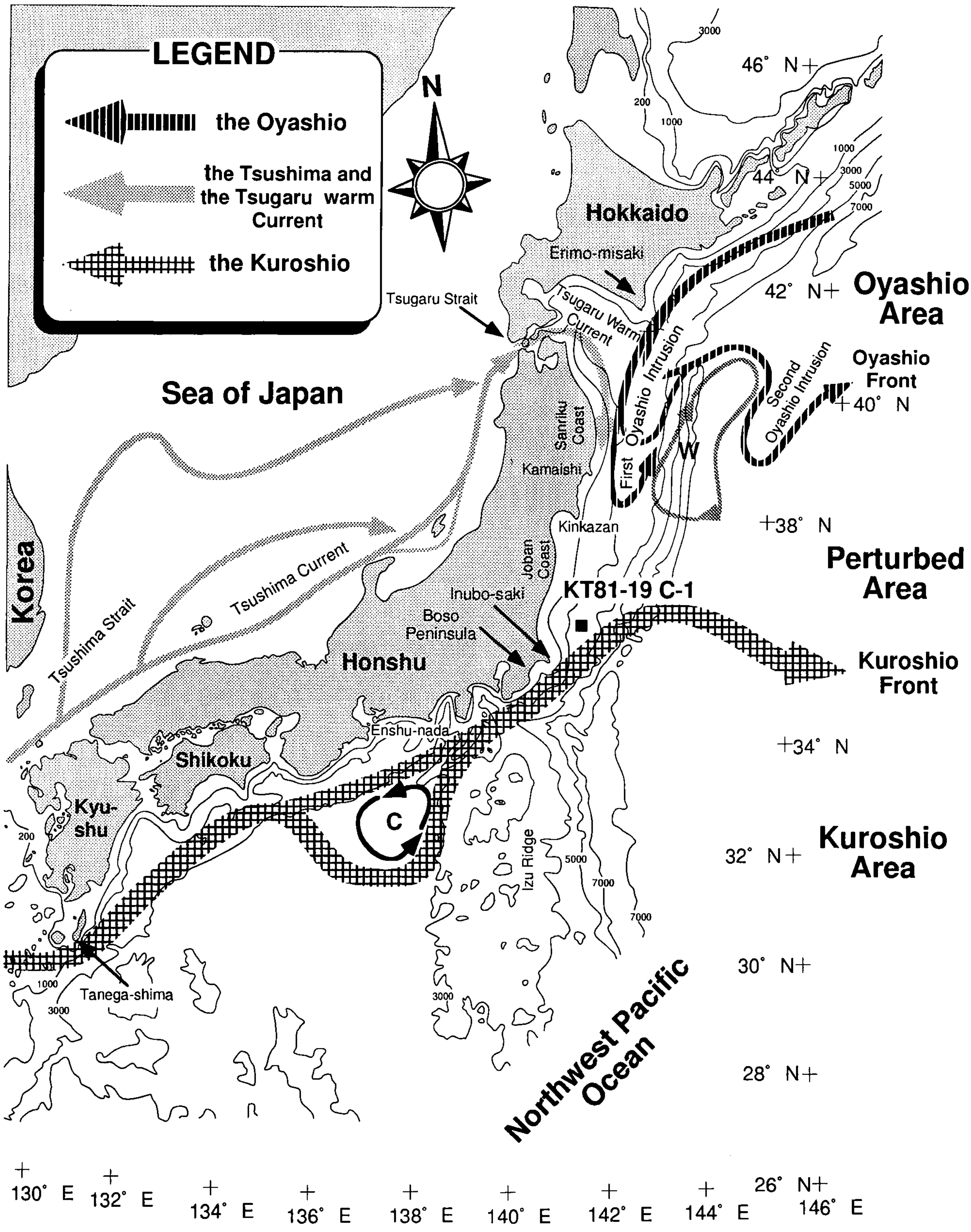
Formulation of Transfer Functions

(1) Samples

Surface sediment assemblages of planktic foraminifera analyzed for this study include those collected off northeast Honshu (Takayanagi and Oda, 1983) and from off southeast Japan (Oda and Takemoto, 1992). Generally, sediment samples from water depth greater than 3,500 m contain foraminiferal assemblages displaying evidence of dissolution; samples yielding foraminifers severely influenced by dissolution were removed from analysis. In the end, 81 surface sediment samples containing modern surface populations were selected from the area off Hokkaido to the area off Tanega-shima, encompassing some 12° of latitude between Lat. 30°N to 42°N (Figure 3, Table 1).

Samples were washed on a 63 μm opening sieve with tap water; sediment residues on the screen were then dried.

Figure 1. Map showing major current systems, the generalized distribution of surface water masses in seas adjacent to the Japanese Islands and a piston core KT81-19, C-1 used in this study.
C: areas dominated by cold water masses during the meandering of the Kuroshio Current, W: areas dominated by warm water masses within the so-called Perturbed Area between the Kuroshio and Oyashio Currents. (Modified after Masuzawa, 1957 and Kawai, 1972).


LEGEND
the Oyashio
the Tsushima and the Tsugaru warm Current
the Kuroshio
N
Hokkaido
Erimo-misaki
Tsugaru Strait
Tsugaru Warm Current
Oyashio Area
Oyashio Front
First Oyashio Intrusion
Second Oyashio Intrusion
W
Sea of Japan
Sanriku Coast
Kamaishi
Kinkazan
Joban Coast
Perturbed Area
Korea
Tsushima Current
Tsushima Strait
Inubo-saki
Boso Peninsula
KT81-19 C-1
Kuroshio Front
Honshu
Enshu-nada
Shikoku
Kyu-shu
C
Izu Ridge
Kuroshio Area
Tanega-shima
Northwest Pacific Ocean
46° N
44° N
42° N
40° N
38° N
34° N
32° N
30° N
28° N
26° N
130° E
132° E
134° E
136° E
138° E
140° E
142° E
144° E
146° E
200
1000
3000
5000
7000

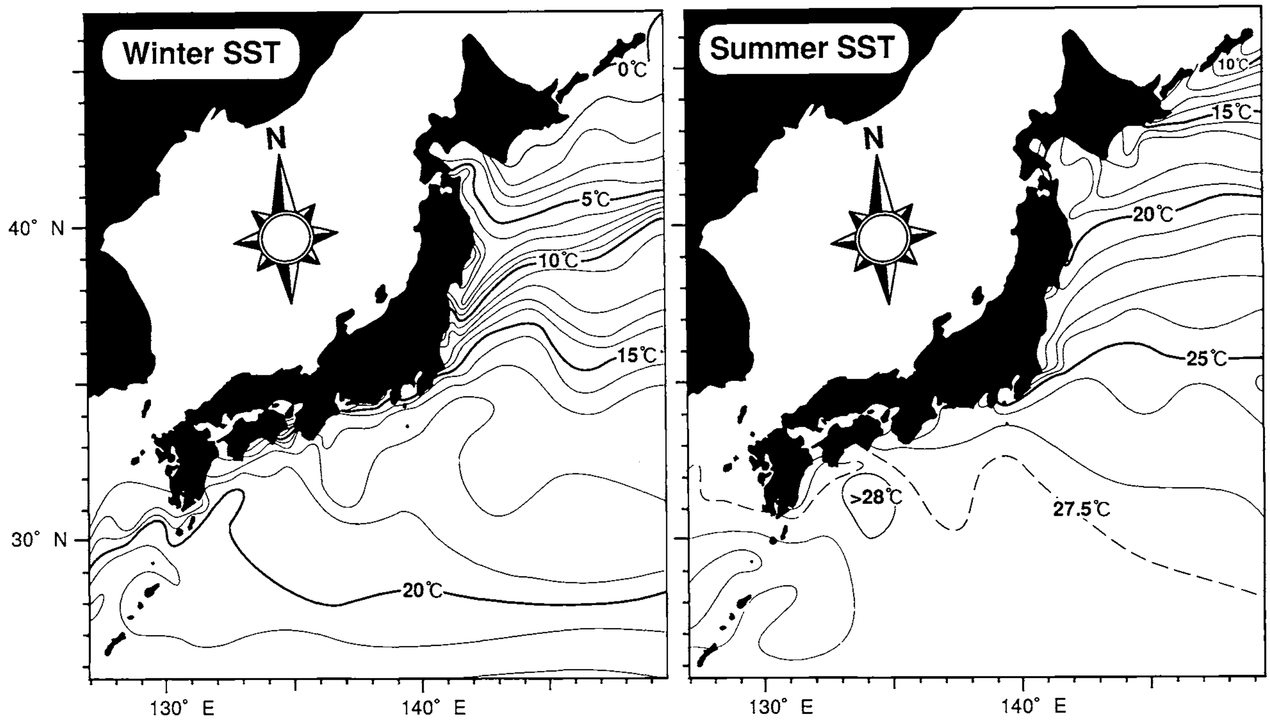


Figure 2. Map illustrating modern winter and summer surface water temperatures in the northwest Pacific Ocean ; temperature values taken from the Marine Environmental Atlas (1978)

Residues were subsequently split with a micro-splitter to yield more than 200 foraminiferal specimens. Each sample aliquot was then sieved through a 125 μm opening screen and all planktic foraminiferal specimens picked from the coarser fraction and identified to species to compile a faunal census. On average, 377 specimens were identified and counted in each sample.

(2) Factor Analysis

Thirty-seven species and 16 genera of planktic foraminifera were recognized in the 81 surface sediment samples analyzed. Twenty-four species assigned to nine genera were selected for Q-mode factor analysis on the basis of their high frequencies (Table 2). Species listed in Table 3 make only a small contribution to the analysis because of their very low frequencies or limited geographic occurrences. The most frequently occurring species (Table 2), on average, account for 98% of the total planktic foraminifera in any given sample.

We recalculated the percentage frequency of each taxon among the 24 most frequent species. We next employed Q-mode factor analysis using the faunal similarities cosine-theta of the 81 surface sediment samples analyzed, following procedures detailed by Imbrie and Kipp (1971). The specific program we utilized is described by Klovan and Imbrie (1971). Computer FUJITSU M1800 of the Computer Center of Kyushu University was used to carry out calculations. The calculated eigenvalues indicate that the first five factors account for more than 94% of the total variance among the samples analyzed (Table 4).

Figures 4-8 illustrate the distribution of the varimax factor loadings (Table 5) when are classified into six categories, e.g. 0.000, 0.138, 0.572 four times and 1.000 as maximum of absolute values. The distribution of each varimax factor loadings is interpreted and correlated with key oceanographic parameters.

The first varimax factor explains 49.44% of the total variance. The first varimax assemblage is dominated by *Globigerinita glutinata* (Egger) and *Globigerina bulloides* d'Orbigny, accompanied by *Neogloboquadrina dutertrei* (d'Orbigny) and *Globigerinoides ruber* (d'Orbigny). The varimax factor loadings show high values in almost all stations south of Lat. 35°N (Figure 4). In contrast, varimax factor loadings display low values in stations north of Lat. 35°N, and especially north of Lat. 38°N. Thus, the distribution of the varimax factor loadings clearly demonstrates that the first factor reflects the relative importance and influence of the Kuroshio water mass on the distribution of planktic foraminifera in the sample analyzed.

Bradshaw (1959) reported that *Globigerinita glutinata* is most abundant in tropical regions but also ranges into subarctic waters. *Globigerina bulloides* has been reported from subarctic cold water to tropical regions (Bradshaw, 1959 ; Tolderlund and Bé, 1971 ; Bé, 1977 ; Reynolds and Thunell, 1985), is reported to feed on phytoplankton, and its production has been shown to rapidly increase in areas of upwelling and phytoplankton blooms in both the Pacific and Atlantic Oceans (Tolderlund and Bé, 1971 ; Thunell and Reynolds, 1984 ; Reynolds and Thunell, 1985). Moreover, *Gnt. glutinata* mainly feeds on diatoms (Hemleben *et al.*,

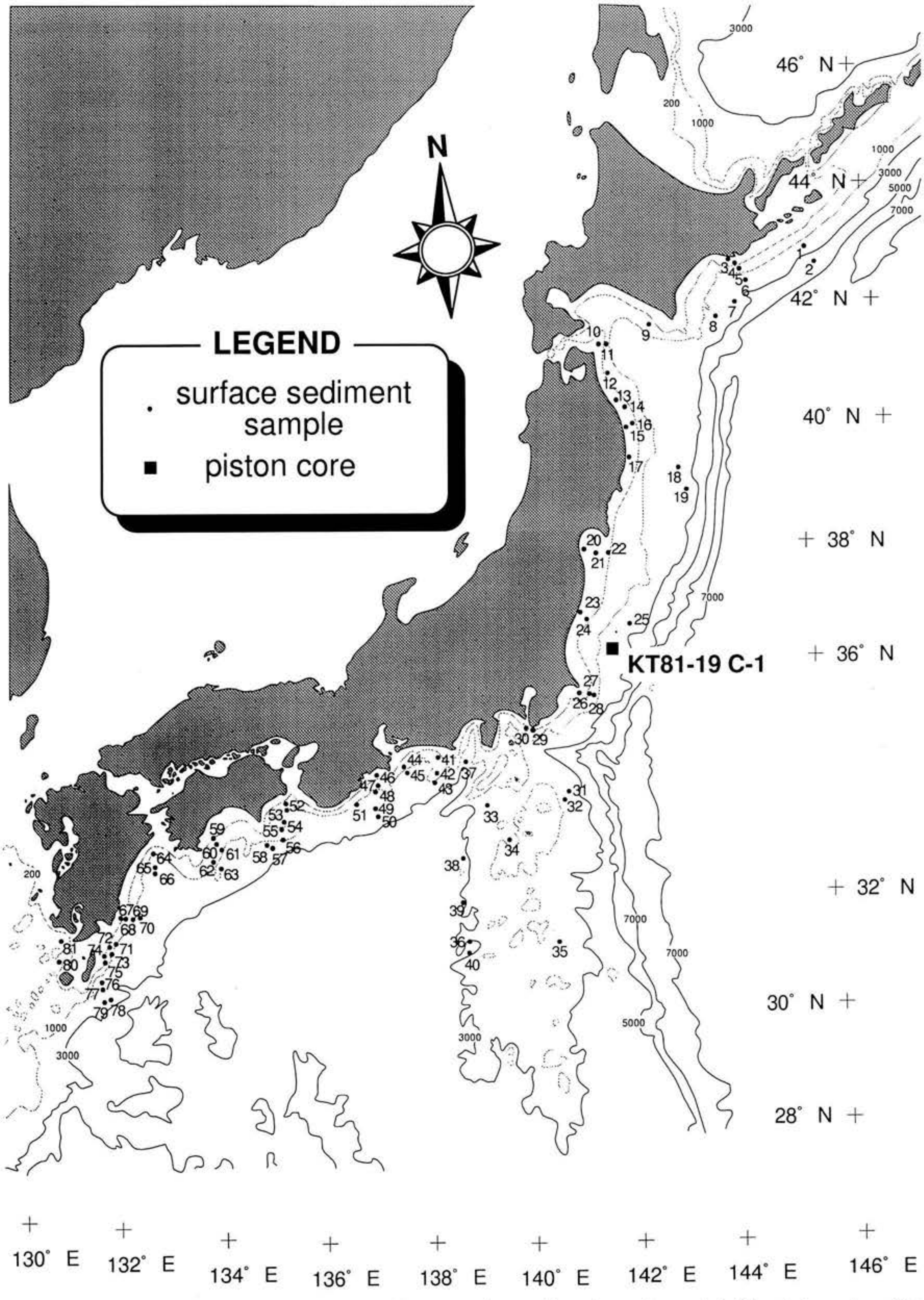


Figure 3. Map illustrating the location sites of the 81 surface sediment sample used in this study and a piston core (KT81-19, C-1) analyzed here.

Table 1. Locations and water depths of surface sediment samples used in study.

	cruise No.	latitude	longitude	depth (m)
1	GH76-2	42°56′	146°20.7′	2,488
2	GH76-2	42°37.9′	146°33.8′	3,383
3	KT78-8	42°53.6′	144°41.5′	53
4	KT78-8	42°45′	144°48.3′	152
5	KT78-8	42°37.7′	144°54.8′	883
6	KT78-8	42°32.1′	144°59.4′	1,530
7	GH76-2	42°06′	144°46.2′	2,195
8	GH76-2	41°56.1′	144°11.1′	1,405
9	KT69-18	41°46.1′	142°39.4′	902
10	KT67-10	41°30′	141°31.9′	70
11	KT67-10	41°30.3′	141°38.8′	598
12	KT69-18	47°59.2′	141°28.8′	300
13	KT69-18	40°41.3′	141°47.5′	100
14	GH76-3-II	40°29.8′	141°57.8′	120
15	GH76-3-II	39°57.0′	142°02.7′	110
16	GH76-3-II	40°01.5′	142°10.8′	150
17	KT70-11	39°22.4′	142°03.2′	120
18	KT70-11	39°15.2′	143°02.9′	1,965
19	KH94-3	38°53.52′	143°22.11′	2,353
20	KT65	37°59′	141°03.3′	38
21	KT65	37°56.5′	141′29.34′	130
22	KT65	37°58.4′	141°42′	185
23	KT75-7	36°49.5′	140°54.3′	30
24	KT75-7	36°40.7′	141°07.5′	160
25	KT95-10	36°40.07′	141°59.94′	2,516
26	KT70-11	35°34.8′	141°02.9′	100
27	KT70-11	35°31.8′	141°13.6′	388
28	KT70-11	35°31.5′	141°14.5′	642
29	GH75-3	34°54′	140°01′	190
30	GH75-3	34°57.5′	139°39.7′	595
31	GH80-4	33°51.9′	140°36.3′	2,160
32	KT86-10	33°40.4′	140°30′	1,693
33	KT86-10	33°37.2′	139°08.6′	1,868
34	KT86-10	33°08.1′	139°24′	1,294
35	GH79-4	30°59.7′	141°04.8′	2,915
36	GH79-4	31°15.3′	138°17.6′	3,680
37	KH74-3	34°20.6′	138°37′	1,423
38	KT92-17	32°40.1′	138°27.3′	3,256
39	KT92-17	31°55.5′	138°25.1′	3,313
40	KT92-17	31°05.7′	138°39.9′	3,335
41	KT85-6	34°26.7′	138°00.1′	495
42	KT85-6	34°10.6′	138°00.0′	938
43	KT85-6	34°01.8′	137°58.1′	1,406
44	KT85-6	34°15.6′	137°16.5′	587
45	KT85-6	34°10.0′	137°21.1′	1,249
46	GH82-2	34°13.3′	136°37.8′	100
47	GH82-2	34°04.7′	136°43.5′	670
48	GH82-2	33°58′	136°41′	1,500
49	GDP-8	33°36.5′	136°44.5′	2,078
50	GDP-8	33°22′	136°50.8′	2,375
51	GH82-2	33°44.2′	136°10.2′	1,217
52	KT81-15	34°30.3′	134°48.2′	720
53	KT81-15	33°26.7′	134°48.1′	1,135
54	GH82-1	33°17.8′	134°41.2′	1,110

Table 1 continue

	cruise No.	latitude	longitude	depth (m)
55	GH82-1	33°09.9′	134°38′	750
56	GH82-1	32°56.5′	134°39′	1,000
57	GH82-1	32°50.4′	134°17.2′	1,500
58	GH82-1	32°49.9′	134°26.6′	1,700
59	KH72-2	32°57.5′	133°21.4′	202
60	KH72-2	32°50.5′	133°26′	475
61	KH72-2	32°43.8′	133°30.4′	808
62	GH83	32°35.3′	133°38.5′	900
63	GH83	32°22.6′	133°47.3′	1,200
64	GH83-2	32°34.4′	132°17.43′	900
65	GH83-2	32°26.49′	132°17.51′	1,482
66	GH83-2	32°21.97′	132°17.60′	1,589
67	GH83-2	31°32.49′	131°32.42′	124
68	GH83-2	31°32.7′	131°41.6′	375
69	GH83-2	31°32.66′	131°50.52′	930
70	GH83-2	31°33.31′	131°55.28′	1,125
71	GH84-3	30°58.22′	131°29.49′	970
72	GH84-3	30°52′	131°22.26′	676
73	GH84-3	30°43.9′	131°24.94′	1,185
74	GH84-3	30°42.61′	131°19.12′	196
75	GH84-3	30°37.95′	131°17.71′	254
76	GH84-3	30°19.18′	131°11.29′	1,520
77	GH84-3	30°11.17′	131°13.87′	1,750
78	GH84-3	30°02.36′	131°30.95′	2,710
79	GH84-3	30°01.48′	131°25.87′	2,309
80	G6K8	31°00.1′	130°24.6′	310
81	G9K15	30°39.9′	130°24.9′	375

1989; Ottens, 1992), and its production is also triggered by upwelling and high phytoplankton productivity bloom, as in the case of *Gna. bulloides* (Thunell and Reynolds, 1984; Reynolds and Thunell, 1985; Sautter and Sancetta, 1992). Thus, it is generally assumed that the distribution of *Gnt. glutinata* and *Gna. bulloides* depends largely on food supply, and that they can tolerate wide ranges in sea surface temperature. *Nqd. dutertrei* and *Gds. ruber*, subordinate species of the characteristic Kuroshio assemblage, are typical warm-water species, widely distributed in tropical and subtropical regions (Tolderlund and Bé, 1971; Bé, 1977). Thus, the composition of the Kuroshio assemblages represents an indicator of relatively warm water accompanied and influenced by seasonal phytoplankton blooms.

The second varimax factor explains 21.67% of the total variance. The second varimax assemblage is characterized by an extraordinarily high contribution of *Neogloboquadrina incompta* (Cifelli) and a subordinate contribution of *Globigerina quinqueloba* Natland. The second factor clearly reflects an association with the Transitional Water between the Oyashio and Kuroshio fronts. The varimax factor loadings show high values in areas extending from the Tsugaru Strait to off Inubo-saki along the Sanriku coast, and in seas off Enshu-nada, northeast Honshu (Figure 5). The former reflects the relative importance of the Tsugaru Warm Current whereas the latter correlates with the area where the Kuroshio meanders, forming the Cold Water Mass. These

Table 2. Planktic foraminiferal species used for factor analysis including their average percentage abundance, standard deviation and maximum abundance (%).

No.	Species	Average	Standard deviation	Maximum occurrence
1	*Globigerina bulloides* d'Orbigny	15.25	9.33	35.67
2	*Gna. falconensis* Blow	3.96	3.73	14.60
3	*Gna. quinqueloba* Natland	6.91	10.25	53.54
4	*Gna. rubescens* Hofker	0.87	1.02	4.09
5	*Globigerinella aequilateralis* (Brady)	0.49	0.62	2.48
6	*Gnl. calida* (Parker)	0.46	1.02	7.70
7	*Globigerinita glutinata* (Egger)	13.67	11.39	38.35
8	*Gnt. iota* Parker	0.93	1.57	7.49
9	*Globigerinoides conglobatus* (Brady)	0.38	0.65	3.74
10	*Gds. ruber* (d'Orbigny)	6.57	4.70	16.26
11	*Gds. sacculifer* (Brady)	1.41	1.75	9.85
12	*Gds. tenellus* Parker	1.00	1.10	5.31
13	*Globorotalia inflata* (d'Orbigny)	5.50	5.35	26.58
14	*Grt. menardii* (Parker, Jones and Brady)	0.39	0.72	3.49
15	*Grt. scitula* (Brady)	0.14	0.29	1.57
16	*Grt. truncatulinoides* (d'Orbigny)	0.41	0.69	3.90
17	*Grt. tumida* (Brady)	0.18	0.55	4.41
18	*Neogloboquadrina dutertrei* (d'Orbigny)	9.99	7.25	34.23
19	*Nqd. incompta* (Cifelli)	13.77	18.33	80.21
20	*Nqd. pachyderma* (Ehrenberg) (D*)	0.37	0.94	4.55
21	*Nqd. pachyderma* (Ehrenberg) (S**)	12.59	27.22	98.68
22	*Orbulina universa* (d'Orbigny)	0.22	0.60	4.95
23	*Pulleniatina obliquiloculata* (Parker and Jones)	4.38	5.36	32.35
24	*Turborotalita humilis* (Brady)	0.17	0.33	1.79

Table 3. Planktic foraminiferal species identified but not used in formulating transfer function Eq. PFJ-125 along with their maximum occurrence (%).

No.	Species	Maximum occurrence
1	*Beella digitata* (Brady)	1.18
2	*Candeina nitida* d'Orbigny	0.07
3	*Globigerinella adamsi* (Banner and Blow)	0.21
4	*Globorotalia bermudezi* Rögl and Bolli	0.93
5	*Grt. hirsuta* (d'Orbigny)	0.93
6	*Globoquadrina conglomerata* (Schwager)	0.77
7	*Hastigerina pelagica* (d'Orbigny)	0.26
8	*Hastigerinopsis riedeli* (Rögl and Bolli)	0.23
9	*Sphaeroidinella dehiscens* (Parker and Jones)	0.47
10	*Tenuitella fleisheri* Li	1.77
11	*Turborotalita anfracta* (Parker)	2.71
12	*Tbt guaymasensis* Matoba and Oda	3.56
13	*Tbt. parkerae* (Brönnimann and Resig)	0.61

particular varimax factor loadings are barely detectable at stations west of Long. 134°E off southeast Japan, where the paths of the Kuroshio do not differ, irrespective of its meandering (Taft, 1972). Therefore, the second varimax factor is an excellent indicator of the Transitional Water, or more specifically, the Tsugaru Warm Current, the Cold Water Mass, or both.

Nqd. incompta is an established indicator of the Tsugaru Warm Current (Oda *et al*., 1983). In addition, high frequencies of *Nqd. incompta* are also present off Enshu-nada

Table 4. Varimax factor score matrix showing the contribution of planktic foraminiferal species to each factor.

	1st factor	2nd factor	3rd factor	4th factor	5th factor
Gna. bulloides	0.569	0.066	0.038	0.108	0.060
Gna falconensis	0.166	0.023	−0.010	−0.002	−0.128
Gna. quinqueloba	0.057	0.308	−0.010	−0.009	0.869
Gna. rubescens	0.040	−0.007	0.000	0.003	0.042
Gnl. aequlateralis	0.019	−0.004	0.000	0.016	−0.013
Gnl. calida	0.024	−0.006	0.001	−0.004	0.015
Gnt. glutinata	0.701	−0.028	0.021	−0.495	−0.065
Gnt. iota	0.039	0.024	−0.006	−0.038	−0.110
Gds. conglobatus	0.010	−0.008	0.001	0.040	−0.002
Gds. ruber	0.239	0.014	−0.010	0.156	−0.018
Gds. sacculifer	0.042	−0.021	0.003	0.109	−0.014
Gds. tenellus	0.045	−0.002	0.002	−0.009	0.034
Grt. inflata	0.099	0.157	−0.013	0.226	−0.384
Grt. menardii	0.012	−0.001	0.000	0.018	−0.027
Grt. scitula	0.003	0.005	−0.001	0.004	−0.013
Grt. truncatulinoides	0.006	0.014	−0.002	0.021	−0.019
Grt. tumida	0.004	0.005	−0.002	0.009	−0.011
Nqd. dutertrei	0.244	−0.012	0.018	0.718	0.082
Nqd. incompta	−0.045	0.929	−0.047	−0.013	−0.222
Nqd. pachyderma (D)	−0.004	0.007	0.022	0.017	−0.008
Nqd. pachyderma (S)	−0.038	0.049	0.997	−0.009	−0.011
Orb. unversa	0.010	−0.001	0.000	0.003	0.001
Pul. obliquiloculata	0.130	−0.084	0.014	0.367	−0.013
Tbt. humilis	0.008	0.002	−0.001	−0.008	−0.009
variance	49.443	21.668	13.166	6.091	3.837
cumulative var.	49.443	71.111	84.277	90.367	94.204

Table 5. The varimax factor loading matrix and communalities for the 81 surface sediment samples from the northwest Pacific Ocean off Japan.

	1st factor	2nd factor	3rd factor	4th factor	5th factor	communality
1	−0.038	0.050	0.997	−0.007	−0.014	0.999
2	0.006	0.092	0.994	0.008	0.019	0.998
3	0.051	0.197	0.968	−0.034	0.133	0.997
4	0.025	0.099	0.991	0.004	0.049	0.995
5	−0.008	0.070	0.997	−0.007	−0.008	0.999
6	−0.027	0.050	0.998	−0.007	−0.010	0.999
7	−0.025	0.054	0.998	−0.006	0.000	0.999
8	0.059	0.072	0.990	0.006	0.020	0.989
9	−0.003	0.711	0.689	0.031	0.009	0.982
10	−0.011	0.955	−0.004	0.009	−0.149	0.935
11	−0.004	0.961	0.095	−0.001	−0.100	0.942
12	0.038	0.961	0.189	−0.002	−0.042	0.963
13	0.009	0.954	0.130	−0.003	0.235	0.983
14	0.096	0.918	0.292	0.015	0.235	0.993
15	0.077	0.943	0.133	−0.001	0.279	0.990
16	0.047	0.893	0.421	0.007	0.096	0.986
17	0.063	0.915	0.263	−0.019	0.275	0.987
18	0.047	0.358	0.899	0.172	−0.117	0.981
19	0.045	0.211	0.970	0.070	−0.066	0.997
20	0.165	0.661	0.080	−0.007	0.693	0.952
21	0.105	0.957	0.093	0.052	0.033	0.940
22	0.112	0.962	0.168	0.095	0.037	0.976
23	0.262	0.564	0.067	0.053	0.728	0.923
24	0.273	0.808	0.130	0.408	−0.189	0.946

Table 5 continue

	1st factor	2nd factor	3rd factor	4th factor	5th factor	communality
25	0.420	0.534	0.180	0.579	−0.106	0.840
26	0.518	0.216	0.016	0.695	0.331	0.907
27	0.782	0.334	0.077	0.368	0.174	0.895
28	0.648	0.722	0.132	0.042	−0.131	0.978
29	0.808	0.321	0.017	0.407	0.031	0.924
30	0.831	0.283	0.021	0.319	0.138	0.891
31	0.877	0.208	0.011	−0.028	−0.203	0.854
32	0.923	0.049	0.024	−0.030	−0.041	0.858
33	0.643	0.535	−0.011	0.115	−0.343	0.831
34	0.953	0.106	0.029	−0.117	−0.124	0.949
35	0.686	0.531	−0.003	0.199	−0.286	0.873
36	0.243	0.793	−0.030	0.368	−0.346	0.944
37	0.551	0.733	−0.009	0.248	−0.223	0.952
38	0.751	0.516	0.007	0.283	−0.232	0.965
39	0.608	0.574	−0.007	0.432	−0.280	0.964
40	0.911	0.279	0.013	−0.097	−0.211	0.962
41	0.625	0.422	0.000	0.498	−0.171	0.845
42	0.693	0.580	−0.001	0.215	−0.149	0.886
43	0.597	0.687	−0.005	0.259	−0.186	0.930
44	0.507	0.750	−0.028	0.022	−0.331	0.930
45	0.681	0.572	−0.009	0.184	−0.280	0.902
46	0.773	0.253	0.023	0.444	0.318	0.960
47	0.951	0.134	0.036	0.164	0.140	0.970
48	0.947	0.248	0.025	0.144	−0.064	0.984
49	0.874	0.176	0.034	0.326	−0.048	0.905
50	0.926	0.186	0.028	0.036	−0.138	0.914
51	0.736	0.569	0.004	0.271	−0.201	0.978
52	0.941	0.254	0.028	0.033	0.190	0.987
53	0.933	0.227	0.030	0.161	0.139	0.969
54	0.938	0.135	0.035	0.170	0.224	0.978
55	0.966	0.128	0.031	−0.127	0.147	0.988
56	0.960	0.149	0.035	0.154	−0.042	0.970
57	0.855	0.343	0.022	0.205	−0.144	0.912
58	0.958	0.176	0.033	−0.093	−0.054	0.961
59	0.870	0.178	0.029	0.359	0.166	0.946
60	0.949	0.183	0.028	0.063	0.102	0.949
61	0.912	0.062	0.042	0.329	0.066	0.949
62	0.963	0.056	0.029	−0.129	0.023	0.948
63	0.955	0.147	0.026	0.189	−0.059	0.974
64	0.961	0.085	0.039	−0.031	0.038	0.935
65	0.945	0.116	0.038	0.205	−0.041	0.952
66	0.946	0.042	0.044	0.111	0.010	0.911
67	0.865	0.166	0.030	0.167	0.420	0.980
68	0.910	0.106	0.037	0.150	0.195	0.902
69	0.990	0.026	0.036	−0.079	−0.004	0.988
70	0.966	0.011	0.033	−0.101	−0.024	0.945
71	0.971	0.014	0.042	0.155	0.004	0.968
72	0.818	−0.010	0.030	0.420	−0.010	0.847
73	0.977	0.027	0.036	0.083	0.047	0.965
74	0.496	−0.032	0.023	0.757	−0.009	0.820
75	0.394	−0.044	0.020	0.755	−0.033	0.728
76	0.957	0.013	0.034	−0.134	−0.034	0.936
77	0.966	0.005	0.033	−0.093	−0.024	0.944
78	0.886	−0.017	0.034	0.309	−0.039	0.883
79	0.927	0.000	0.035	0.234	−0.068	0.920
80	0.943	0.079	0.033	0.136	0.179	0.948
81	0.968	0.030	0.035	0.150	0.036	0.962

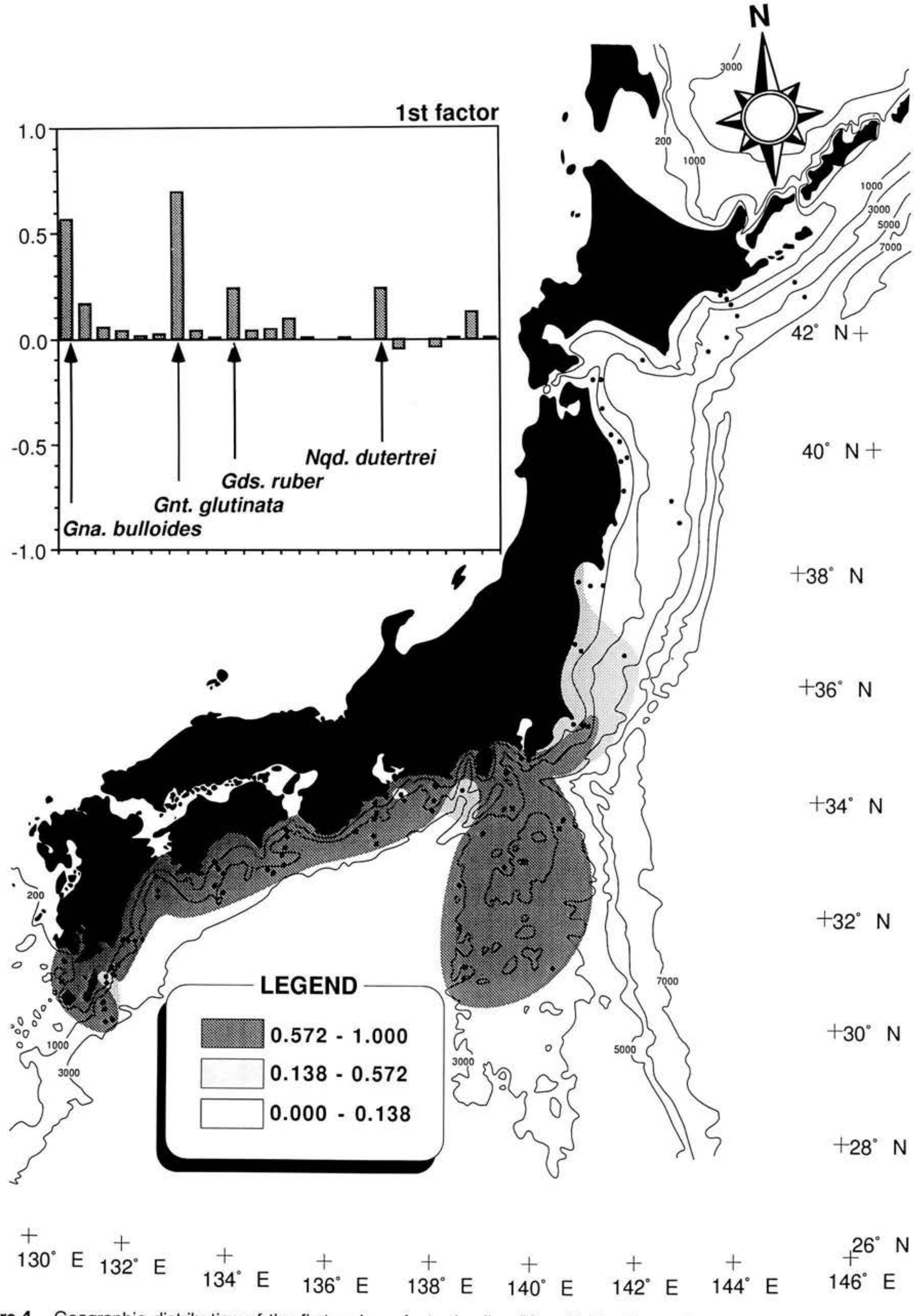


Figure 4. Geographic distribution of the first varimax factor loading (Kuroshio) in the northwest Pacific Ocean off Japan.

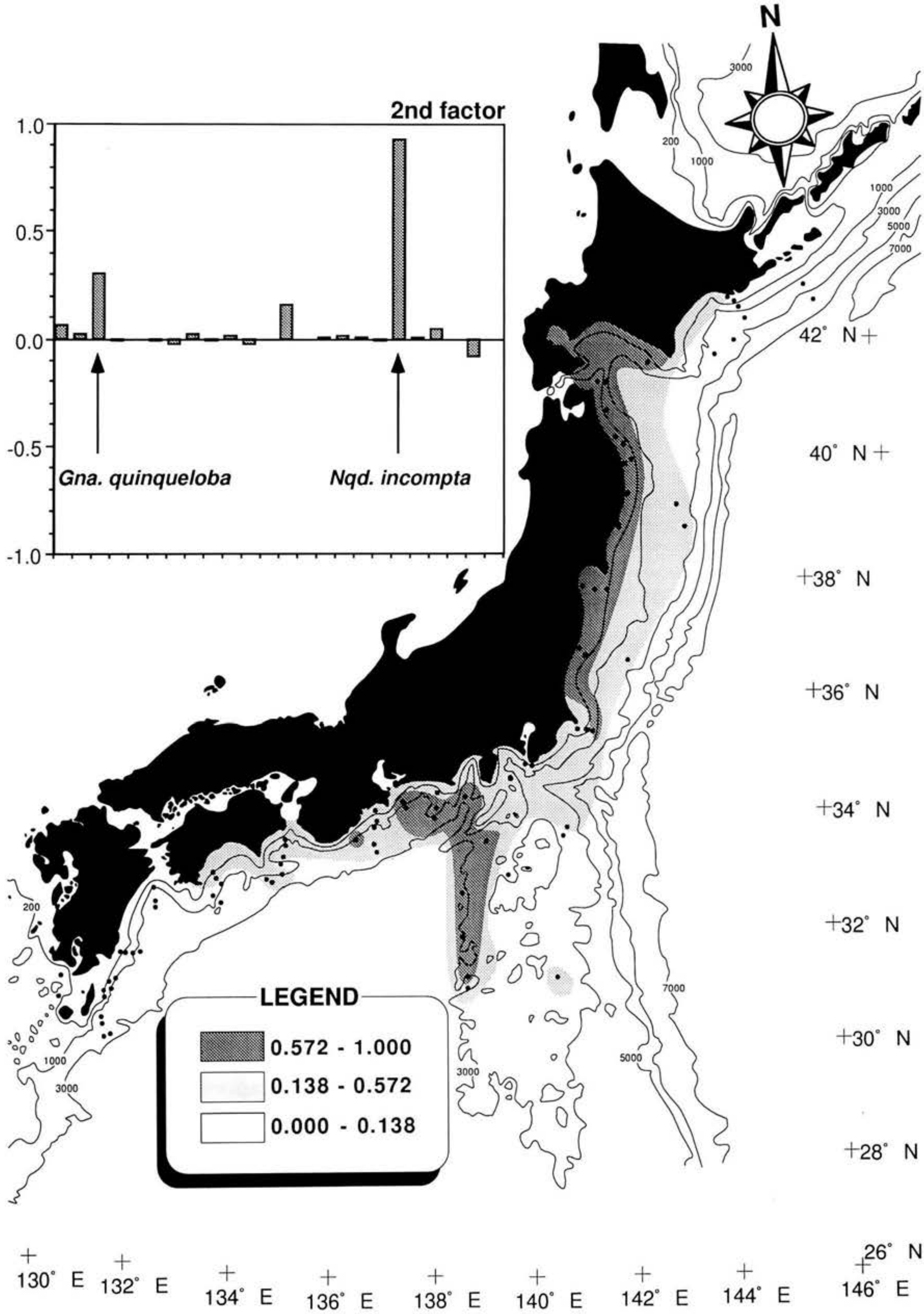


Figure 5. Geographic distribution of the second varimax factor loading (Transitional) in the northwest Pacific Ocean off Japan.

where the Cold Water Mass frequently occurs. Since the southern limit of the Tsugaru Warm Current is at approximately Lat. 38°N, near Kinkazan Island and the northern limit of the Cold Water Mass is at approximately Lat. 34°N off Enshu-nada these two water masses are geographically isolated from each other. The former is characterized by the occurrence of the sinistral form of *Neogloboquadrina pachyderma* (Ehrenberg) (given as *Nqd. pachyderma* (S)), whereas this species is not present in the latter water mass. Consequently, we conclude that there are two possible influences on the assemblage, the Tsugaru Warm Current and the Cold Water Mass, with a possible distinction based upon the occurrence of *Nqd. pachyderma* (S).

The third varimax factor explains 13.17% of the total variance. The third varimax assemblage is represented by only one species, *Nqd. pachyderma* (S). Figure 6 shows the varimax factor loadings which are apparently high to the north of the Oyashio Front as might be anticipated. Thus, the third factor reflects an association with the cold Oyashio Current.

Nqd. pachyderma (S) is the dominant species of cold water (Reynolds and Thunell, 1985; Sautter and Thunell, 1989) in polar and subpolar regions (Bradshaw, 1959; Bé, 1977; Tolderlund and Bé, 1971). This species has also been regarded as a typical indicator species of the Oyashio Current near Japan (Takayanagi and Oda, 1983; Oda *et al.*, 1983; Chinzei *et al.*, 1987).

The fourth varimax factor explains 6.09% of the total variance. The fourth varimax assemblage is composed of such tropical species as *Nqd. dutertrei* and *Pulleniatina obliquiloculata* (Parker and Jones). Figure 7 shows the varimax factor loadings which have high values at stations off the Joban coast (Lat. 36°40′N), off Inubo-saki (Lat. 35°35′N), and around Tanega-shima Island (Lat. 30°60′N), and have middle values at stations off the Pacific coast of southeast Japan. Stations north of Lat. 37°N show very little influence of the fourth varimax factor except for one station where warm core eddies frequently occur. Accordingly, the fourth varimax factor suggests an association with the Kuroshio Gyre Margin.

The fifth varimax factor explains 3.84% of the total variance. The fifth varimax assemblage is again represented by only one taxon, *Gna. quinqueloba*. The varimax factor loading shows high values along the Joban coast in the Perturbed Region (Figure 8), while low values are recognized in the coastal area from off southeast Kyushu to off southeast Shikoku. The distribution of the fifth factor loadings suggests the degree to which particular oceanic regions can be influenced by coastal influences, for instance, increasing mixing with low-salinity waters.

Gna. quinqueloba is abundant in coastal areas including shelf areas off Japan and shows a propensity for low-salinity areas (Wang *et al.*, 1988; Takayanagi and Oda, 1983). Thus, the distribution of the fifth varimax factor loadings expresses the influence of Coastal Water.

(3) Regression Analysis

Multiple regression analysis was used to verify the relationship between the planktic foraminiferal data set and oceanographic data within the study area, and subsequently used to formulate multiple regression equations. The oceanographic data set includes average surface water temperatures for both the summer and the winter taken from the Marine Environmental Atlas (the Japan Oceanographic Data Center, 1978). The planktic foraminiferal data set includes the five varimax assemblages identified in 81 surface samples. The program ANALYST was used to carry out the multiple regression analysis using the FACOM operation system of the Computer Center of Kyushu University.

The following two transfer functions, termed Equation PFJ-125, yield surface water temperatures (SST) for the winter and the summer:

SST in the winter is given by

(1) $Tw = 5.49x_1 - 4.65x_2 - 10.93x_3 + 2.59x_4 - 4.81x_5 + 13.71$, R^2(contribution)$=0.92$, standard error$=1.75$°C.

SST in the summer is given by

(2) $Ts = 4.16x_1 - 2.28x_2 - 6.50x_3 + 1.23x_4 - 3.41x_5 + 23.74$, R^2(contribution)$=0.92$, standard error$=1.17$°C.

Note that x_1 to x_5 indicate the proportions of the varimax loadings.

To ascertain the reliability of the equation in estimating sea surface temperature, we applied calculated values derived for each of the foraminiferal samples analyzed and compared the estimated values with observed SST values (Figure 9). The standard error of estimated winter SST is about 8.92% of the present SST range (0.7〜20.3°C) and about 8.96% of the present summer SST range (15.0〜28.1°C). Standard ANOVA F-statistics are shown in Table 6. For each equation, the correlation coefficient squared is greater than 0.9, and the standard error is less than 9.0% of the total range. Thus, these equations yield SST values of apparent accuracy and precision.

Estimated Variations in Downcore Surface Temperature Value

Piston core KT81-19 C-1 (243 cm in length), obtained from the sea bottom beneath the Perturbed Region north of the Kuroshio Front (water depth of 1,545 m; Lat. 36°15.9′N, Long. 141°1.8′E) off the Joban coast of Northeast Honshu, Japan (Figure 1), was selected to test the reliability of equations in estimating paleo-SST. The bottom of this core was estimated by Chinzei *et al.* (1987) to be younger than 12,000 yrs. B.P. based on radiocarbon dating of two horizons and five tephra key beds. Oda and Takemoto (1992) studied planktic foraminiferal assemblages from 41 sediment samples taken at 5 cm sampling intervals through core KT81-19 C-1, with a time resolution of 163-383 yrs. The method of sample preparation and treatment was identical to that applied to surface sediment samples analyzed for this study.

Down-core fluctuations in winter and summer SSTs calculated by the equations discussed above span the last 12 Kyrs, where the first through fifth factor loadings represent the proportions of the first five varimax assemblages (Figure 10). Communalities of all the samples are higher than 0.7 and average 0.92 (Table 7).

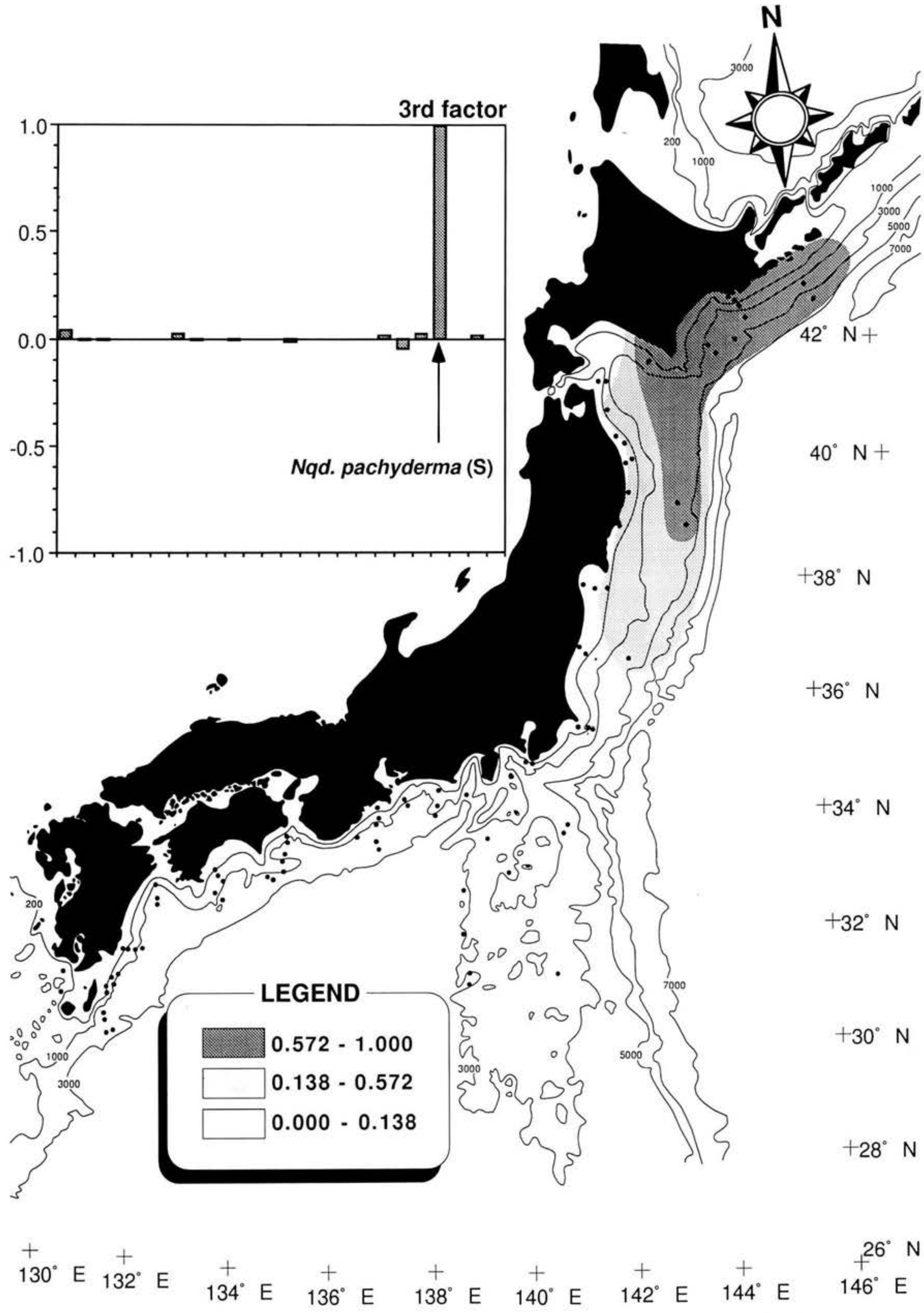


Figure 6. Geographic distribution of the third varimax factor loading (Oyashio) in the northwest Pacific Ocean off Japan.

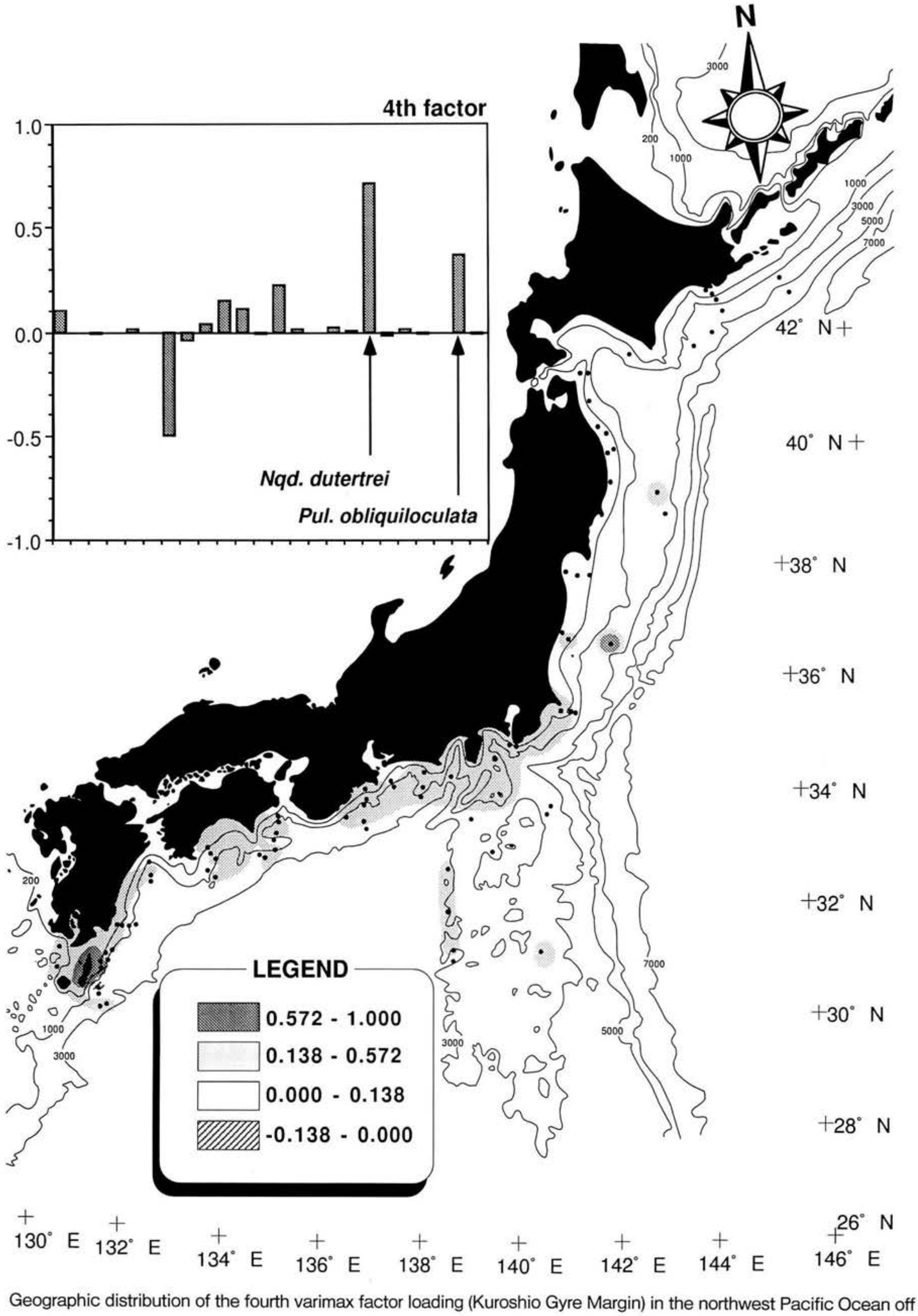


Figure 7. Geographic distribution of the fourth varimax factor loading (Kuroshio Gyre Margin) in the northwest Pacific Ocean off Japan.

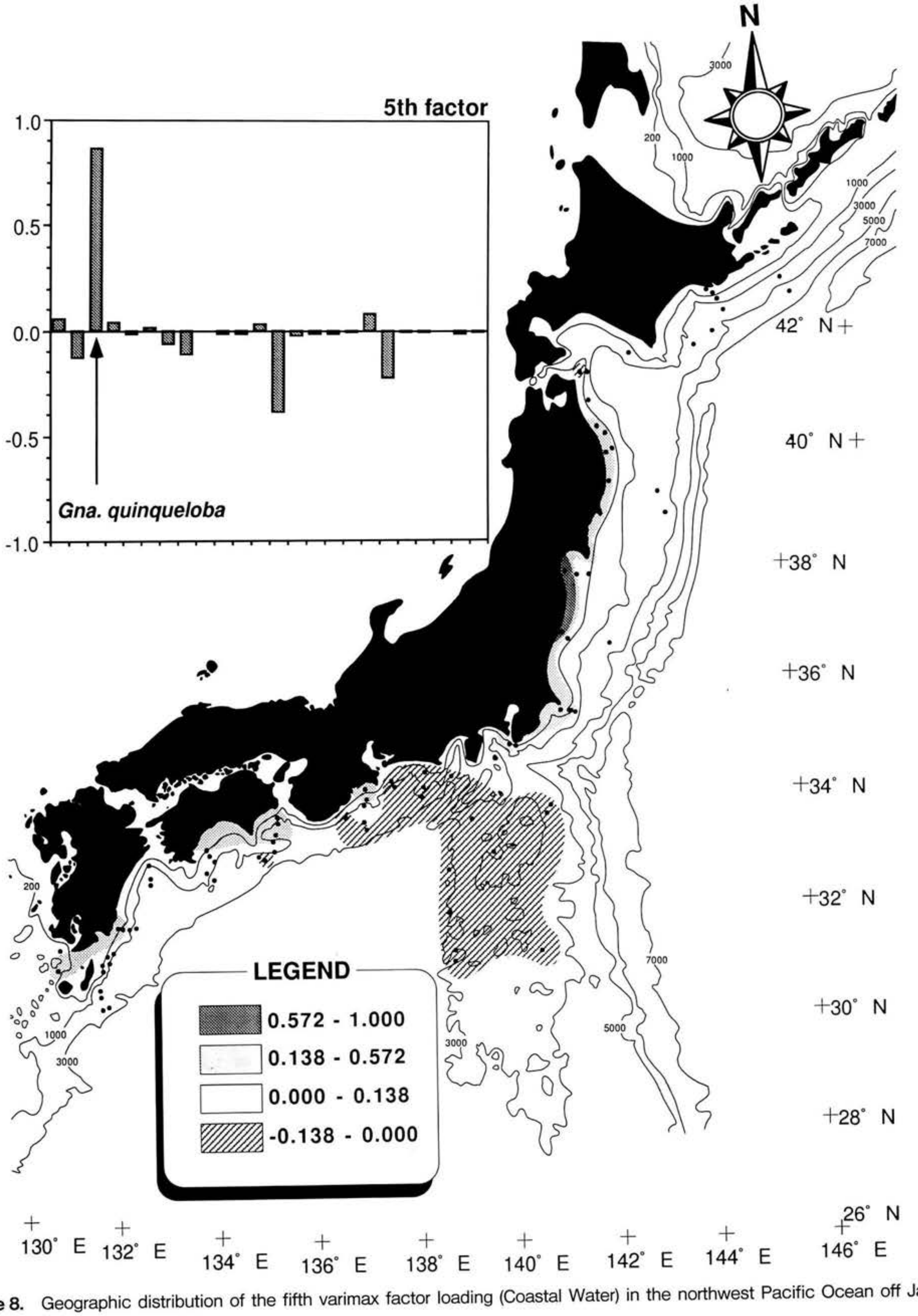


Figure 8. Geographic distribution of the fifth varimax factor loading (Coastal Water) in the northwest Pacific Ocean off Japan.

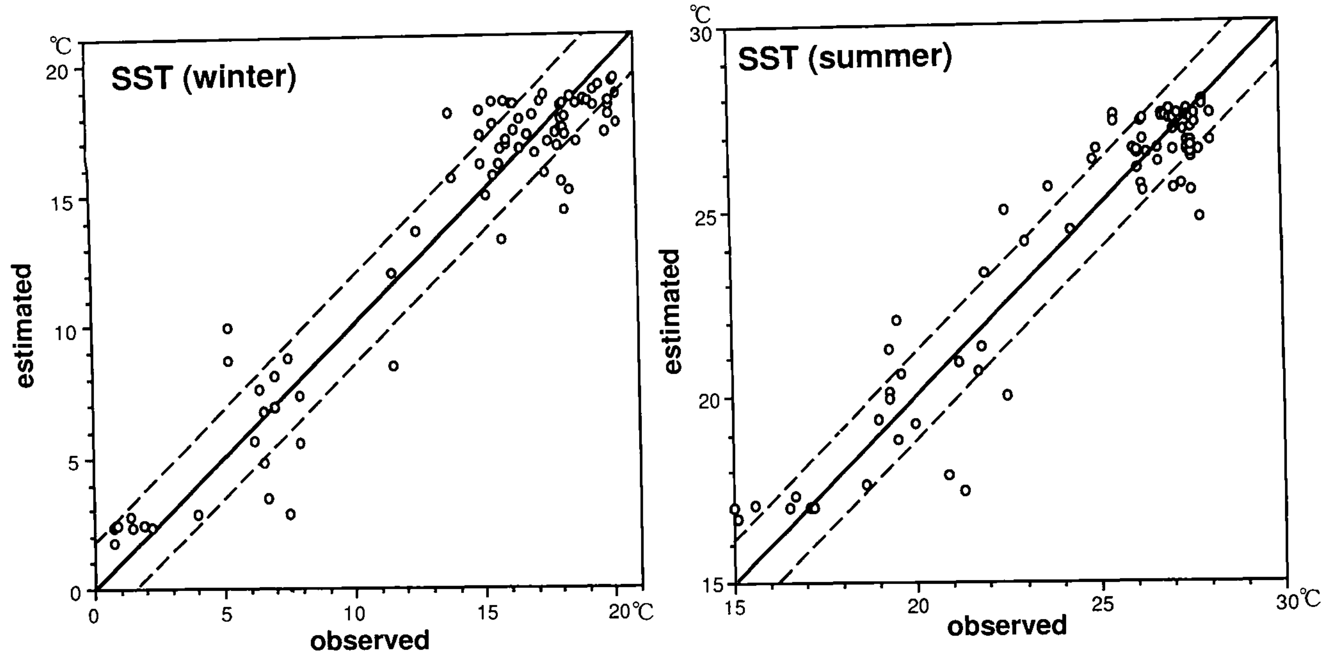


Figure 9. Comparison of observed winter and summer sea surface temperatures (SST) in the northwest Pacific Ocean off Japan and estimated SST derived through application of the paleontological transfer functions PFJ-125, Tw and Ts. Broken lines denote the limit of standard errors.

Table 6. ANOVA F-statistics for equations Ts and Tw.

	Standard error	sum of square	degree of freedom	unibiased variance	F-value
Ts	1.17				
regression		1,126.82	5	225.36	163
residual		103.40	75	1.38	
total		1,230.22	80	15.38	
Tw	1.75				
regression		2,749.76	5	549.95	180
residual		229.31	75	3.06	
total		2,979.07	80	37.24	

Estimated sea surface temperatures (SST) down core KT81-19 C-1 indicate the coldest period at approximately 10,500 yrs. B.P. (about 3.9°C in the winter and 18.5°C in the summer). After 10,000 yrs B.P., there are indications of a slight warming of SST with a radical increase in SST at 8,000 yrs. B.P. (about 6.9°C in the winter and 20.3°C in the summer.). This latter warming trend displays a peak at 6,300 yrs. B.P. (12.8°C in the winter and 23.9°C in the summer.). After 6,000 yrs. B.P., the SST decreased gradually, with a warming peak again at 3,100 yrs B.P. (about 12.6°C in the winter and 23.8°C in the summer). After 3,000 yrs. B.P., two cooling peaks centered at about 2,200 yrs. B.P. and 1,300 yrs. B.P. can be recognized (7.9°C and 7.2°C in the winter, 20.9°C and 20.4°C in the summer, respectively), with a final warming peak centered at about 1,800 yrs. B.P. (11.8°C in the winter and 23.4°C in the summer).

The coldest estimated winter and summer SSTs (c.a. 10,500 yrs. B.P.) in this core are similar to values of the modern ocean off cape Erimo (Erimo-misaki), southern Hokkaido. It is noteworthy that the difference in winter SST at 10,500 yrs.B.P. and that for the modern winter in this area is about 8°C.

Discussion

The validity of the computed SST values downcore to 11,000 yrs. B.P. for core KT81-19 C-1 can be examined by comparing the distribution of each of the varimax factor loadings (Figure 10).

The most significant fluctuations in factor loadings include the distinctive dominance of the third (Oyashio) factor between 11,000 and 8,000 yrs B.P., the decline of the Oyashio factor after 8,000 yrs B.P., a peak of the first (Kuroshio) factor at 6,300 yrs B.P., and an increase of the second (Transitional

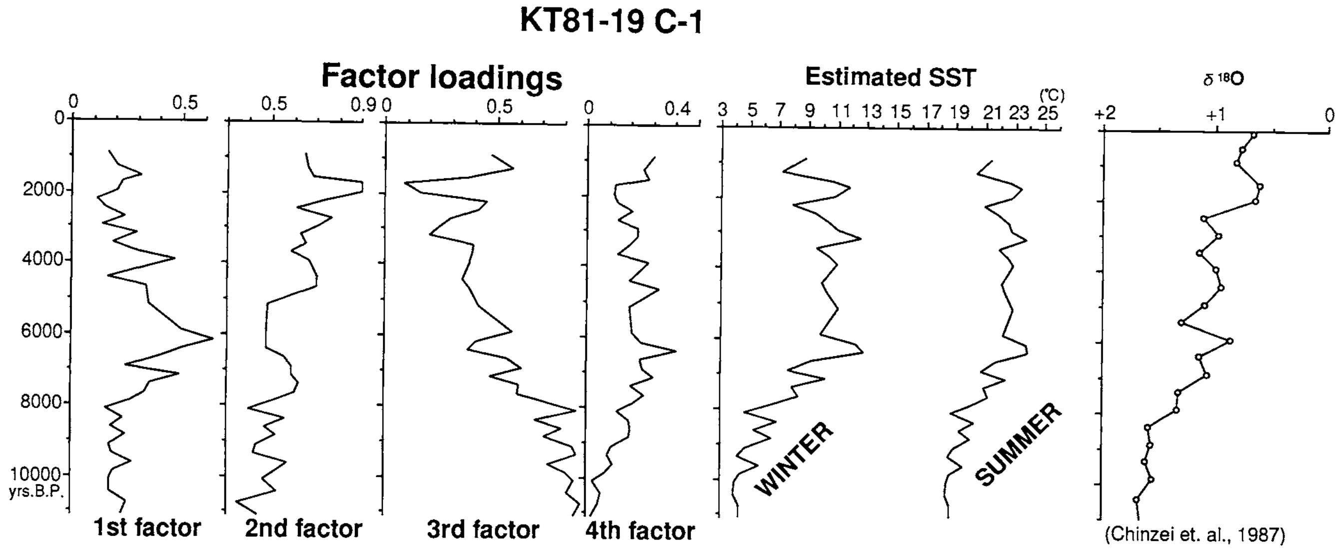


Figure 10. Estimated winter and summer sea surface temperatures (°C) down core KT 81-19, C-1 as analyzed using the paleontological transfer functions PFJ-125, with the first four varimax factor loadings ; $\delta^{18}O$ curve based on analyses of the planktic foraminifera *Grt. inflata* (from Chinzei *et al.*, 1987).

Water) factor after 5,000 yrs B.P. These fluctuations are thought to express northward and/or southward shifts of the Kuroshio Front in the region off Japan.

The Oyashio factor dominated during 11,000-8,000 yrs. B. P. Estimated SST values are low during the latter period, with the lowest SST about 3.9°C in the winter and 18.5°C in the summer at 10,500 yrs B.P. These estimates of the winter and summer temperatures are close to those values for the modern Oyashio water off Erimo-misaki, southern Hokkaido, which is situated 5° north of the C-1 core site. Thus, we conclude that the Oyashio Front was near the C-1 core site during this period.

Although the Oyashio factor decreased rapidly after 8,000 yrs B.P. the Kuroshio factor began to increase and peaks at 6,300 yrs. B.P. The increase in amplitude of the estimated SST is about 8.2°C in winter and 5.2°C in summer between 8,000-6,000 yrs. B.P. At 6,300 yrs. B.P., corresponding to the peak in the Kuroshio factor, the estimated winter and summer SST reached their maxima of 12.8°C and 23.9°C, respectively, representing an especially distinctive winter maximum. These estimations of the winter and summer temperatures are close to the modern SST values of the Kuroshio frontal zone off Point·Inubo (Inubo-saki, Lat. 35°70′N). Furthermore, an increase of the fourth Kuroshio Gyre margin factor preceded the increase in Kuroshio factor, showing a peak at 6,400 yrs. B.P. Thus, we assume that the increase in the Kuroshio Gyre margin factor indicates a northward shift of the Kuroshio Front.

Thus, the decreasing values of the Kuroshio factor indicates a southward shift of the Kuroshio Front after 6,300 yrs. B.P. Almost simultaneously, there is a general increase in the proportion of the Transitional Water factor after 5,000 yrs. B.P. We assume that the core C-1 site region was influenced by the Transitional Water, especially, the Tsugaru Warm Current at that time. Influence of the Tsugaru Warm Current has continued to the present in this area, although our estimated SST values indicate short warm peaks at 3,100, 2,200, 1,800 and 1,200 yrs B.P. These latter events are thought to reflect the influence of the Oyashio Factor because of varimax factor loadings.

Chinzei *et al.* (1987) analyzed oxygen isotopes in the planktic foraminifer *Grt. inflata* in piston core C-1. The resulting oxygen isotope records display a trend of heavier values downcore and a sharp shift toward the heaviest value of $\delta^{18}O$ in the basal part of the core. This same record indicates an episode of cooling around 10,500 yrs. B.P. and a warm trend around 7,000-6,000 yrs. B.P. which peaked at 6,300 yrs. B.P. The results of this study generally agree with those of Chinzei *et al.* (1987). In particular, both studies recognize an episode of cooling at about 10,500 yrs. B.P., followed by a warming trend, and a warm maximum at 6,300 yrs. B.P. Chinzei *et al.* (1987) also suggested that the cooling episode recorded at 10,500 yrs. B.P. was likely correlated with the Younger Dryas cool period. These same authors also concluded that the water temperature maximum at 6,300 yrs. B.P. likely reflected the arrival of the Kuroshio Front at the C-1 core site.

The earliest cool episode in core C-1, which corresponds to the horizon of heaviest values of $\delta^{18}O$ in the lowest part of this core, indicates a cooling of surface water in the Perturbed Area by about 8°C (both winter and summer), with SST values close to those of the modern Oyashio water off Erimo-misaki, southern Hokkaido. The difference between the estimated winter SST at 10,500 yrs. B.P., an averaged modern winter sea surface temperature at this site, and the composition of the planktic foraminiferal assemblage are collectively viewed as evidence of the southward penetration of the Oyashio Current. Marine conditions during this latter cooling episode recorded in core C-1 are comparable to those of the last glacial maximum, based upon the southward penetration of the Oyashio Current off Japan at 18,000 yrs. B.P. and average modern February sea surface tempera-

Table 7. Varimax factor loading matrix for core C-1.

yrs.B.P.	1st factor	2nd factor	3rd factor	4th factor	5th factor	communality
88	0.165	0.645	0.467	0.303	−0.325	0.860
1270	0.207	0.658	0.564	0.255	−0.191	0.900
1557	0.313	0.679	0.354	0.280	−0.330	0.870
1719	0.231	0.897	0.082	0.129	−0.318	0.980
1966	0.205	0.895	0.156	0.120	−0.315	0.980
2212	0.114	0.732	0.450	0.141	−0.320	0.870
2458	0.149	0.608	0.414	0.202	−0.372	0.740
2704	0.240	0.765	0.289	0.142	−0.366	0.880
2951	0.136	0.706	0.243	0.226	−0.400	0.790
3197	0.296	0.624	0.198	0.226	−0.368	0.700
3443	0.189	0.648	0.393	0.188	−0.348	0.770
3689	0.286	0.586	0.386	0.139	−0.353	0.720
3936	0.463	0.661	0.376	0.275	−0.248	0.930
4428	0.160	0.699	0.343	0.191	−0.377	0.810
4675	0.336	0.701	0.375	0.327	−0.246	0.910
5167	0.346	0.481	0.418	0.192	−0.369	0.700
5906	0.496	0.473	0.567	0.208	−0.256	0.900
6152	0.637	0.473	0.404	0.250	−0.218	0.900
6399	0.501	0.475	0.366	0.401	−0.310	0.870
6645	0.396	0.556	0.541	0.243	−0.256	0.880
6892	0.246	0.591	0.607	0.253	−0.276	0.920
7139	0.489	0.592	0.471	0.301	−0.190	0.940
7386	0.357	0.621	0.596	0.199	−0.221	0.960
7632	0.333	0.600	0.588	0.259	−0.277	0.960
7879	0.273	0.505	0.722	0.211	−0.232	0.950
8126	0.156	0.400	0.855	0.138	−0.190	0.970
8373	0.237	0.560	0.669	0.195	−0.275	0.930
8619	0.181	0.473	0.790	0.197	−0.203	0.960
8866	0.248	0.516	0.712	0.192	−0.233	0.930
9113	0.172	0.434	0.835	0.112	−0.203	0.970
9360	0.186	0.424	0.858	0.099	−0.119	0.970
9606	0.276	0.575	0.730	0.123	−0.163	0.980
9853	0.192	0.517	0.807	0.082	−0.124	0.980
10100	0.176	0.461	0.841	0.033	−0.117	0.970
10433	0.175	0.524	0.814	0.066	−0.087	0.980
10767	0.253	0.347	0.873	0.055	−0.049	0.950
11100	0.229	0.442	0.842	0.027	−0.100	0.970

tures as indicated by Moore *et al.* (1980) and Thompson (1981). Thus, the 10,500 yrs. B.P. cooling episode represents a dramatic event in the northwest Pacific on the same scale as the Last Glacial Maximum when the steepest gradient was developed between subarctic and subtropical waters off northeast Honshu, Japan.

Summary

(1) Planktic foraminifera were quantitatively analyzed in eighty-one surface sediment samples collected at deep sea stations off Japan in the northwestern Pacific Ocean. Two hundred or more specimens were identified and counted in each sample and census data used for Q-mode principal components factor analysis. Species selected include 24 taxa belonging to 9 genera. The calculated eigenvalues indicate that the first to fifth factors, which account for more than 94% of the total variance, correspond to a Kuroshio factor, a Transitional Water factor, an Oyashio factor, a Kuroshio Gyre Margin factor and a Coastal Water factor, respectively.

(2) The varimax factor loadings of the first five factors were used as explanatory variables; modern winter and summer surface temperatures (SSTs) values. Each equation derived by this analysis shares multiple correlation coefficients greater than 0.9, and standard errors of less than 9.0% of the total range. Transfer functions, which we term Equation PFJ-125, were derived from regression analysis of planktic foraminiferal assemblages to observed SST values. The transfer functions have a standard error of 1.75°C in estimating winter SST and 1.17°C in estimating summer SST.

(3) Application of transfer functions PFJ-125 to planktic foraminiferal assemblages in piston core C-1 representing the last 12 K yrs in the Perturbed Area off Joban, northeast

Honshu (Lat. 36°15.9′N, Long. 141°31.8′E), discloses a cool episode at 10,500 yrs. B.P. with a winter SST of about 3.9°C and a summer SST of about 18.5°C. A warm peak occurred at 6,300 yrs. B.P. with a winter SST of about 12.8°C and summer SST of 23.9°C. The difference in SST values between winter 10,500 yrs. B.P. and average modern winter at the C-1 core site is about 8°C, essentially equivalent to values of modern Oyashio Current water off Erimo-misaki, southern Hokkaido, or about five degrees of latitude north of the core C-1 site. Thus, marine conditions 10,500 yrs. B.P at core site C-1 off Honshu, Japan were comparable to those established for the last glacial maximum in this area and provide evidence of a southward shift of the Kuroshio and Oyashio Fronts.

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