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High-resolution records of thermocline in the Okinawa Trough since about 10000 aBP

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Abstract The present paper uses planktonic foraminifera and their stable isotopes to study the changes in the depth of thermocline (DOT) in the Okinawa Trough since the last 10000 a based on the analysis of Core B-3GC in the northern Okinawa Trough, together with that of the core in the southern Okinawa Trough. As results show, the thermocline was shallow before 6400 aBP, and deepened afterward, then became shallow again from 4000 to 2000 aBP. The DOT fluctuations display a positive correlation with those of sea surface temperature (SST). In addition, the changes in the northern Okinawa Trough are similar to those in the southern trough, implying a possible connection with the variation of the Kuroshio Current. The changes of SST and DOT suggest that the Kuroshio Current changed its intensity or main axis from 4000 to 2000 aBP and around about 6400 aBP respectively. Moreover, the changes of DOT from 8200 to 6400 aBP may indicate a gradual intensification of the Kuroshio Current.

Keywords: Okinawa Trough, depth of thermocline (DOT), sea surface temperature (SST), Kuroshio Current, planktonic foraminifera, stable isotopes.

The development of modern oceanography has increased the awareness of the climate importance of the air-sea exchange [1]. Generally, only the water above the thermocline can actively exchange with the atmosphere outside the high latitude areas, and, hence, the depth of thermocline (DOT) is one of the important factors to control the climate changes. Besides, the thermocline also controls the distribution of nutrient and plankton in the ocean, and DOT has become one of the foci in paleoceanography. In the last few years, the changes of DOT have been studied using different microfossils and their stable isotopes below and above the thermocline[2—9], while such researches are just beginning in China.

As a part of the western Pacific marginal seas, the Okinawa Trough plays an important role in paleoceanography. The evolution of the Kuroshio Current and its branches is one of the most important paleoceanography subjects in the Okinawa Trough. Higher sea surface temperature (SST) and deeper DOT are characteristic of the Kuroshio area, contrasting with the lower SST and shallower DOT in the continental shelf[10—12]. Therefore, the study of DOT changes is helpful for explaining both the changes of SST and the Kuroshio Current. For this purpose, Core B-3GC from the northern Okinawa Trough was selected for the analyses of planktonic foraminifera and stable isotopes, and the results were compared with those from the southern Okinawa Trough in an attempt to reconstruct the history of DOT and Kuroshio changes during the last 10000 a.

1 Material and methods

1.1 Material

This work was mainly based on Core B-3GC, taken during the Japan B094-20 cruise in 1994 from the continental slope of northern Okinawa Trough (128° 31.14′E, 31° 29.37′N, water depth 555 m; fig. 1), to the east of Tushima Warm Current, a branch of the Kuroshio Current. The core is 218 cm in length, and composed of homogeneous brownish silty clay with no visible turbidities but much volcanic ash between 110 and 150 cm. A total of 84 samples were analysed between 8 and 218 cm in the core at an interval of 2.5 cm.

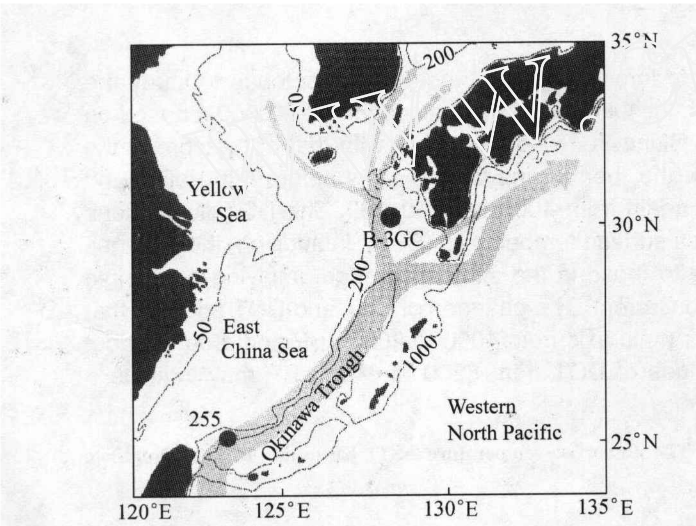

Fig. 1. Location of Cores B-3GC and 255 discussed in this study. Shadow arrows show the Kuroshio Current and its branches (modified from Xu et al.[13]).

The sample analyses followed the standard microfossil technique. About 200 to 500 planktonic foraminiferal tests were picked from the coarse fraction (>0.154 mm) for each sample after splitting into a workable size. Thirty planktonic foraminiferal species were identified and counted. Well-preserved specimens of *Globigerinoides ruber* and *Pulleniatina obliquiloculata* were picked from almost every sample, for the stable isotope analysis at the Graduate School of Environmental Earth Science, Hokkaido University, Japan (table 1, table 2). In addition, well-preserved specimens of *Neogloboquadrina dutertrei* were picked at 10 cm interval for AMS ^{14}C analysis at the Quaternary Isotope Laboratory, Washington University, USA.

Table 1 Information on the geochemical analyses of Core B-3GC

Items	Planktonic foraminiferal species	Test size/mm	Test number	Interval/cm	Sample number
Oxygen and carbon stable isotopes	*G. ruber*	0.35—0.50	>20	2.5	82
	P. obliquiloculata	0.50—0.70	>20	2.5	84
AMS ^{14}C ages	*N. dutertrei*	>0.154	>1000	10.0	22

1.2 Methods for the DOT study

(i) Paleoecology. According to modern ecological researches, the distribution of planktonic foraminifera is closely related to the water depth and DOT[2—4,15,16]. Generally, *Globorotalia*

Table 2 The stable isotope data from planktonic foraminifera in Core B-3GC

Depth/cm	$\delta^{18}O$		$\delta^{13}C$		Depth /cm	$\delta^{18}O$		$\delta^{13}C$		Depth /cm	$\delta^{18}O$		$\delta^{13}C$	
	ruber	*obl.*	*ruber*	*obl.*		*ruber*	*obl.*	*ruber*	*obl.*		*ruber*	*obl.*	*ruber*	*obl.*
9.25	−1.83	−1.30	0.99	0.85	79.25	−2.12	−1.23	1.22	0.96	149.25	−1.88	−0.74	0.75	0.97
11.75	−2.05	−1.05	1.07	0.91	81.75	−2.12	−1.13	1.25	1.01	151.75	−2.05	−0.75	0.66	1.01
14.25	−1.87	−1.01	1.05	0.91	84.25	−1.90	−1.20	1.20	0.92	154.25	−1.87	−0.65	0.87	0.95
16.75	−1.84	−0.94	1.10	0.95	86.75	−1.88	−1.27	1.23	1.00	156.75	−1.90	−0.53	0.73	1.06
19.25	−1.81	−1.13	1.03	0.87	89.25	−1.73	−1.22	1.10	1.03	159.25	−2.01	−0.71	0.71	0.95
21.75	−2.09	−1.00	1.02	0.92	91.75	−1.94	−1.16	1.15	0.95	161.75	−2.07	−0.79	0.69	0.94
24.25	−1.99	−1.09	0.93	0.94	94.25	−1.71	−0.96	1.45	1.05	164.25	−1.92	−0.61	0.61	0.98
26.75	−1.83	−1.37	1.03	0.89	96.75	−2.14	−1.34	1.08	0.88	166.75	−2.12	−0.64	0.67	0.90
29.25	−2.16	−1.05	0.90	0.99	99.25	−1.96	−1.09	0.98	0.98	169.25	−1.65	−0.62	0.69	0.95
31.75	−1.84	−0.79	0.98	1.03	101.75	−2.03	−1.20	1.25	0.97	171.75	−1.71	−0.73	0.81	0.88
34.25	−1.95	−1.27	1.15	0.80	104.25	−1.82	−1.22	0.93	0.98	174.25	−1.99	−0.54	0.56	0.98
36.75	−2.11	−0.90	0.91	1.06	106.75	−1.88	−1.07	0.94	0.97	176.75	−2.06	−0.55	0.72	0.91
39.25	−2.30	−0.85	1.18	0.95	109.25	−2.16	−0.80	0.93	1.06	179.25	−2.12	−0.61	0.60	0.93
41.75	−1.88	−0.82	1.10	1.05	111.75	−1.73	−0.79	0.95	1.03	181.75	−1.84	−0.58	0.57	0.82
44.25	−2.13	−0.81	1.17	0.97	114.25	−2.09	−0.73	0.97	1.00	184.25	−1.51	−0.66	0.57	0.83
46.75	−2.01	−0.67	1.05	1.09	116.75	−2.08	−0.92	1.03	0.98	186.75	−1.65	−0.61	0.58	0.90
49.25	−2.04	−1.06	1.12	0.97	119.25	−2.09	−0.75	0.73	1.04	189.25	−1.57	−0.46	0.77	0.89
51.75	−1.80	−0.81	1.19	1.10	121.75	−2.17	−0.77	0.62	0.98	191.75	−1.83	−0.58	0.51	0.92
54.25	−2.25	−1.00	1.16	1.00	124.25	−2.17	−0.67	0.82	0.94	194.25	−1.66	−0.38	0.54	0.88
56.75	−2.18	−0.99	1.13	1.04	126.75	−2.09	−0.95	0.72	0.87	196.75	−1.71	−0.39	0.55	0.84
59.25	−2.26	−0.78	1.25	1.07	129.25	−2.23	−0.79	0.67	0.91	199.25	−1.58	−0.33	0.60	0.86
61.75	−2.44	−0.92	1.08	1.07	131.75	−2.36	−0.81	0.66	0.95	201.75	−1.80	−0.26	0.63	0.97
64.25	−1.78	−0.85	1.28	1.05	134.25	−2.23	−0.89	0.65	0.95	204.25	−1.67	−0.31	0.48	0.84
66.75	−2.06	−0.6	1.10	1.03	136.75	−2.08	−0.88	0.67	0.99	206.75	−1.83	−0.30	0.62	0.88
69.25	−2.22	−0.95	1.06	1.10	139.25	−2.04	−0.85	0.65	0.91	209.25	−1.58	−0.43	0.56	0.93
71.75	−1.99	−0.94	1.02	1.08	141.75	−1.91	−0.69	0.71	0.94	211.75	−1.86	−0.32	0.55	0.79
74.25	−1.77	−1.11	0.99	0.99	144.25	−2.23	−0.86	0.84	0.98	214.25		−0.25		0.82
76.75	−1.86	−1.21	1.11	0.93	146.75	−1.91	−0.83	0.64	0.96	216.75		−0.25		0.80

ruber represents *G. ruber*; *obl.* represents *P. obliquiloculata*.

menardii, *Neogloboqudrina pachyderma* and *N. dutertrei*, which are called deep-dwelling species, dwell under the thermocline in middle and low latitude areas. When the DOT becomes deeper, these species' living space becomes restricted and their relative abundance decreases. On the otherhand, such species as *Globigerinoides sacculifer*, *G. ruber*, *Globigerinita glutinata* are called shallow-dwelling species, and dwell above the thermocline. Their percentages will increase when the thermocline deepens. Therefore, the relative abundance of the two groups of species can be used as proxies of the DOT[2−4,8,9]. Recently, a planktonic foraminiferal transfer function for estimating DOT was established by Anderson and Ravelo based on 189 surface samples and surveyed DOT in the Pacific Ocean, with a standard error of 27 m [6].

(ii) Isotopes. Stable isotopes can also be used to study the changes of DOT[6]. Generally, *G. ruber* dwells in the water shallower than 50 m, while *P. obliquiloculata* lives in the water around the thermocline[2−4,14,15]. Therefore, their difference in oxygen isotope $|\Delta\delta^{18}O|$ ($|\delta^{18}O_{G.ruber}-\delta^{18}O_{P.\ obliquiloculata}|$) can represent the thermal gradient of the upper (mixing zone) seawater if the salinity does not change greatly. When the DOT decreases, the thermal gradient of upper water will increase, and the value of $|\Delta\delta^{18}O|$ increases accordingly. On the contrary, when the DOT deepens, the temperature of the thermocline water will be close to that of shallow water, and the value of $|\Delta\delta^{18}O|$ will decrease[6]. Because there was no large river around the northern Okinawa Trough during the Holocene, the value of $|\Delta\delta^{18}O|$ affected by the input of fresh water is negligible. The main factor controlling the value of $|\Delta\delta^{18}O|$ during the Holocene is the thermal difference between the surface and thermocline waters. Thus, the value of $|\Delta\delta^{18}O|$ can be used as a proxy of the DOT. In addition, the upper ocean's mixing is also a factor affecting the DOT. Generally, if the mixing of upper ocean is strong, the heat is easy to be transported into deeper water[16], which further leads to deeper thermocline. Otherwise, the DOT becomes shallow. Because $\delta^{13}C_{G.ruber}$ and $\delta^{13}C_{P.\ obliquiloculata}$ represent the distribution of $\delta^{13}C$ in the upper water, their difference $|\Delta\delta^{13}C|$ ($|\delta^{13}C_{G.\ ruber}-\delta^{13}C_{P.\ obliquiloculata}|$) can be used as a proxy indicating the degree of mixing in the upper water. If the value decreases, it is suggested that the degree of mixing in the upper water strengthens and the DOT becomes shallower[6].

2 Results

2.1 Chronology

The 22 AMS ^{14}C ages with a high quality (table 3) are used to construct the chronology of Core B-3GC. These ages are very well distributed in order down the core from young to old. They also coincided in time with the geological events, such as *Pulleniatina obliquiloculata* Event[8,17—19] and K-Ah Event[20] which occurred from about 4000 aBP to 2000 aBP and at 6300 aBP, respectively. According to the chronology of this core, the age of the bottom is about 9500 aBP, and the average sampling resolution is about 110 years. This is the first core in the Holocene section of the East China Sea to have such a high-resolution stratigraphy with datings.

Table 3 AMS ^{14}C age datings of Core B-3GC[a)]

Depth/cm	AMS ^{14}C age/aBP	Error / ±a	Depth/cm	AMS ^{14}C age/aBP	Error / ±a
0—10	210	60	110—120[c)]	6130	60
10—20	450	70	120—130[c)]	6790	60
20—30	1380	60	130—140[c)]	6980	60
30—40[b)]	2390	60	140—150[c)]	6970	60
40—50[b)]	2660	60	150—160	7440	60
50—60[b)]	3140	60	160—170	7700	60
60—70[b)]	3620	60	170—180	8230	70
70—80[b)]	3930	60	180—190	8490	60
80—90	4090	60	190—200	8670	60
90—100	4950	70	200—210	9150	60
100—110	5490	60	210—218	9410	60

a) These ages are not converted into calendar ages. b) *P. obliquiloculata* Minimum Zone (*P. obliquiloculata* Event). c) Abundant volcanic ash (K-Ah Event).

2.2 DOT changes in the northern Okinawa Trough since 10000 aBP

Based on planktonic foraminifera and their stable isotopes, the DOT in the northern Okinawa Trough is reconstructed using the above-introduced methods. According to the changes of DOT, the last 10000 a in this area can be divided into four phases as follows (fig. 2).

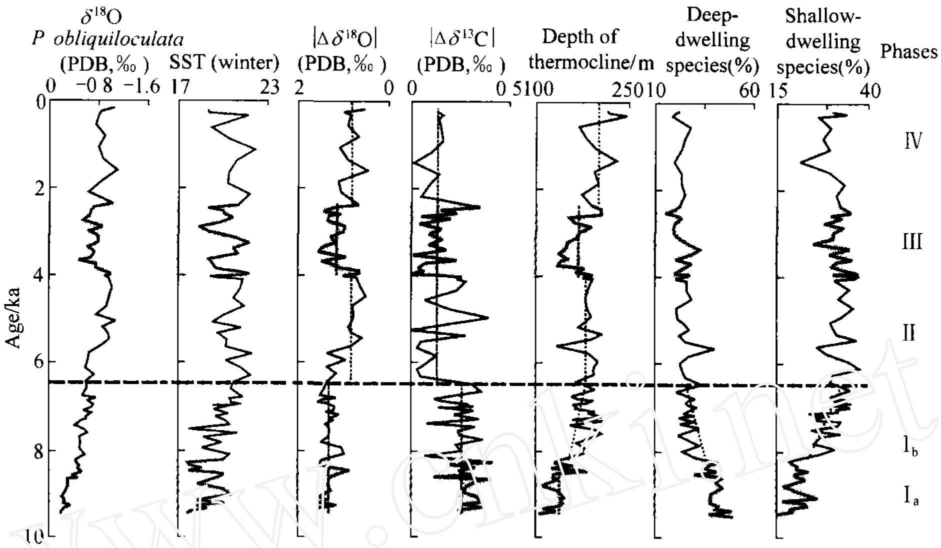

Fig. 2. Down-core variations in the DOT proxies and SST. Shadow areas show the shallow-thermocline phases. The upper one corresponded to the *P. obliquiloculata* Minimum Zone. Vertical and inclined dashed lines indicate the average values and the trend of changes, respectively.

Phase I (9400—6400 aBP). During this phase, the $|\Delta\delta^{18}O|$ and $|\Delta\delta^{13}C|$ values were higher, suggesting a shallower DOT. This phase can be divided into two sub-phases: I_a (from 9400 to 8200 aBP) and I_b (from 8200 to 6400 aBP). I_a is a shallow-thermocline stage. The estimated DOT was generally lower than 160 m. During this sub-phase, the abundance of shallow-dwelling species was very low, while those of deep-dwelling species had the highest value for the last 10000 aBP. I_b is a stage during which the estimated DOT gradually became deep, the abundance of shallow-dwelling species increased while those of deep-dwelling species decreased, also indicating an increasing tendency of the DOT.

Phase II (6400—4000 aBP). The average value of $|\Delta\delta^{18}O|$ was 0.9‰, lower than those during Phases I and III. The average value of $|\Delta\delta^{13}C|$ was only 0.1‰, much lower than that of Phase I. The average estimated DOT was as deep as 184 m. All these proxies suggested that the DOT was very deep during this phase.

Phase III (4000—2300 aBP). The *P. obliquiloculata* Event (about 4000 to 2000 aBP)[8,17—19] just occurred in this phase. During this phase, $|\Delta\delta^{18}O|$ was distinctly high, with an average value of 1.14‰. The estimated DOT ranges from 135 to 180 m, with an average of 169 m. All this indicates that the thermocline was shallow during this period.

Phase IV (2300 aBP—present). During this phase, all the average, minimum and maximum values of $|\Delta\delta^{18}O|$ were lower than those during the other three phases. The estimated DOT was also deep. That is to say, Phase IV was another deep-thermocline phase besides Phase II over the last 10000 a in the northern Okinawa Trough.

3 Comparisons and discussion

Based on the planktonic foraminifera in Core 255 (123° 07′N, 25° 12′E, water depth 1575 m, see fig. 1 for location), the history of DOT changes in the southern Okinawa Trough can also be divided similarly into four phases like in Core B-3GC (fig. 3). Before 6400 aBP, the percentages of shallow-dwelling species were low while those of deep-dwelling species were high, indicating a shallow DOT during this phase. After this phase, the abundance of shallow-dwelling species increased, and deep-dwelling species decreased, both suggesting that the DOT became deeper. During the *P. obliquiloculata* Event, corresponding to Phase III in Core B-3GC, the abundance of *Florisphaera profunda* was distinctly low, since this is a deep-dwelling calcareous nannofossil species which sensitively responds to the changes of the upper water structure[7]. Its low abundance indicates that the DOT greatly decreased during Phase III. As for Phase IV, the results of Core 255 are similar to those of Core B-3GC. However, the changes of DOT in the northern Okinawa Trough are somewhat different from those in the southern Okinawa Trough, especially during Phase I. In the northern Okinawa Trough, Phase I could be divided into two sub-phases (fig. 2) while there is no similar record in the southern Okinawa Trough (fig. 3). This difference possibly resulted from the very low sedimentation rate between 9000 and 6400 aBP in Core 255, and it is hard to distinguish the two sub-phases there. Further work is needed to confirm whether the DOT deepened from 8200 to 6400 aBP in the southern Okinawa Trough.

According to fig. 2, we found that the changes of DOT were correlative with those of SST in the northern Okinawa Trough. During Phases I and III, the DOT became shallow while the estimated SST decreased. When the thermocline deepened, the SST increased accordingly. It was also the case in the southern Okinawa Trough according to Core 255 (fig. 3). Before 6400 aBP and

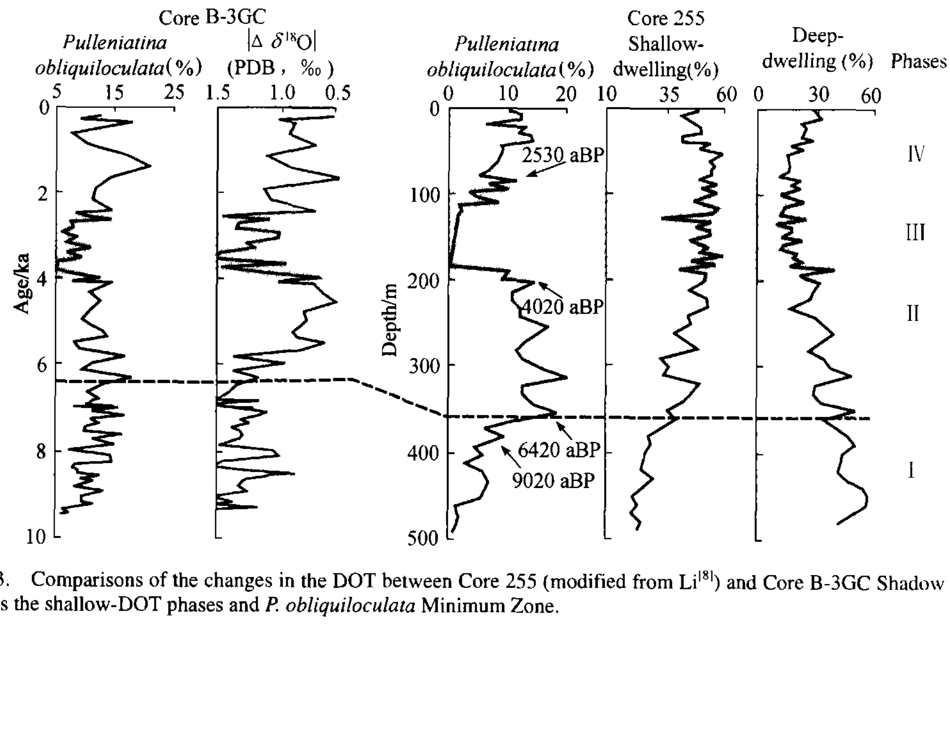

Fig. 3. Comparisons of the changes in the DOT between Core 255 (modified from Li[8]) and Core B-3GC Shadow area shows the shallow-DOT phases and *P. obliquiloculata* Minimum Zone.

from 4000 to 2000 aBP when the DOT was shallow, the abundance of *P. obliquiloculata* was relatively low, indicating low-SST. As to the other two deep-thermocline phases, the SST was relatively high in the core[17—19].

The variations of DOT and SST in the Okinawa Trough are largely controlled by the evolution of the Kuroshio. As mentioned above, the high SST and salinity and deep DOT are characteristic of the Kuroshio[10—12]. When the Kuroshio strengthened in the Okinawa Trough, the SST would increase and the DOT deepened. Otherwise, the SST would decrease and the thermocline shoaled. Based on the changes in microfossil faunas and sediments, the axis and strength of Kuroshio changed for several times since the last glacial maximum stage. The strength of Kuroshio remarkably decreased in the Okinawa Trough during the last glacial maximum, and its axis could even migrate away from the Okinawa Trough. The coastal water then became the main factor controlling the upper water structure in there, giving rise to a lower SST and shallower DOT. After about 6400 aBP, the Kuroshio in the Okinawa Trough greatly strengthened with its axis moved into the Trough again[8,17—19,21,22], resulting in an increase of SST and DOT. The DOT became shallow again between 4000 and 2000 aBP, when the Kuroshio weakened or migrated eastward. Thus, this study presents a new approach to reconstructing the history of Kuroshio in the Okinawa Trough. Although up to now the gradual deepening of DOT and increasing of SST from 8200 to 6400 aBP was found only in Core B-3GC, it still implies a possible gradual intensification of the Kuroshio in the Okinawa Trough. The significant intensification of the increase of the Kuroshio took place right after 6400 aBP because the axis of the Kuroshio migrated into the Okinawa Trough again.

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