Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Marine Micropaleontology 49 (2003) 3–20

MARINE MICROPALEONTOLOGY

www.elsevier.com/locate/marmicro

Sedimentation of planktonic foraminifera in the East China Sea: evidence from a sediment trap experiment

Makoto Yamasaki*, Motoyoshi Oda

Institute of Geology and Paleontology, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

Received 4 June 2001; received in revised form 3 October 2002; accepted 20 January 2003

Abstract

The particle flux from sediment traps moored in the East China Sea from the continental shelf to the Okinawa Trough between 25 February 1993 and 22 February 1994 was analyzed for particle transport processes based on planktonic foraminifera. Conventional sediment traps were moored at points from the continental shelf to the shelf edge. These experiments revealed that benthic foraminifera occurred along with planktonic foraminifera, with contained mud, particularly in sediment traps moored at 10–40 m above the bottom. This finding implies that surface sediment resuspension from the sea bottom is active in this region. In addition, time-series sediment traps were deployed in the Okinawa Trough at three depths (606, 813 and 1017 m) under the main stream of the Kuroshio Current. The total planktonic foraminiferal flux increased with increasing depth and was associated with very few benthic foraminiferal specimens in the two deeper traps. However, planktonic foraminiferal tests filled with mud as seen in traps on the continental shelf were not found in the three traps. This observation suggests that the planktonic foraminifera did not originate in the sediments of the continental shelf and were likely carried laterally during settling. Furthermore, based on comparing the species composition of the foraminiferal flux for the Okinawa Trough station with that for the shelf edge in late October, planktonic foraminifera were considered to arrive at the deeper traps in the Okinawa Trough from the Kuroshio front area which was characterized by high productivity.

Keywords: East China Sea; foraminifera, lateral transport; Kuroshio

---

1. Introduction

In order to better reconstruct paleoenvironmental changes using fossil foraminifera in sediments, the geographic distribution and ecology of living planktonic foraminifera as well as their settling to the seafloor, must be known. Therefore, a time-series sediment trap, which directly collects settling particles in the water column, is an effective instrument to help understand the sedimentation processes for planktonic foraminiferal tests.

The East China Sea is a typical marginal sea with one of the widest continental shelves in the world, and with enormous amounts of freshwater discharged from the Chang Jiang River. The Kuroshio flows throughout the year along the shelf

---

* Corresponding author. Fax: +81-22-217-6612.
E-mail address: yamasaki@mail.cc.tohoku.ac.jp
(M. Yamasaki).

0377-8398/03/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0377-8398(03)00024-0

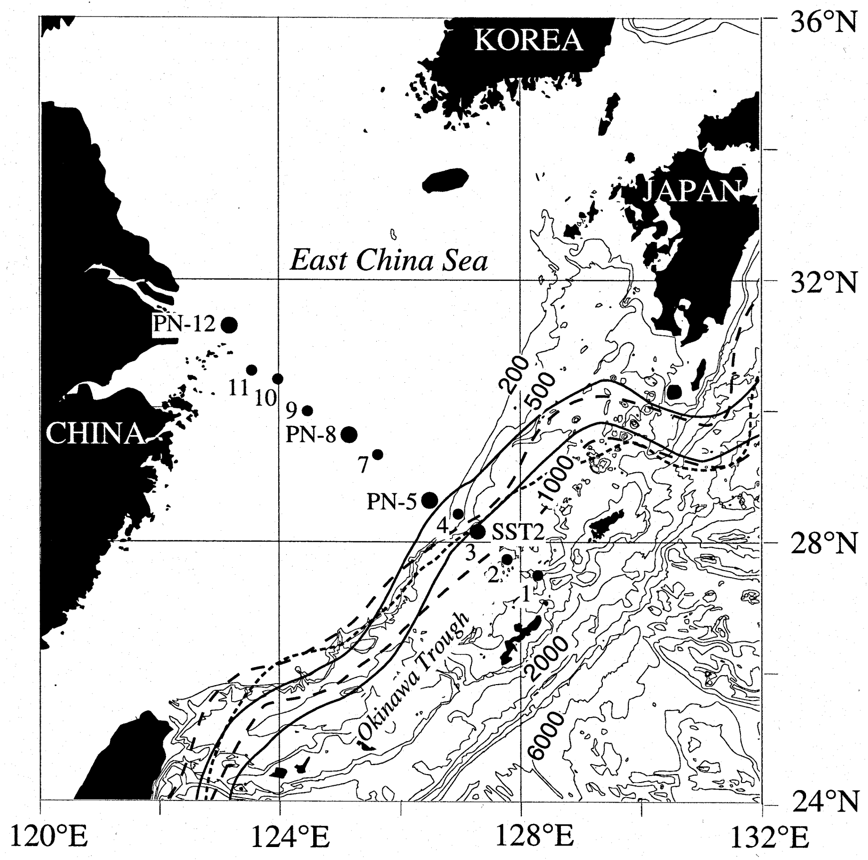


Fig. 1. Locations of sediment traps in the East China Sea. The main stream of the Kuroshio in autumn 1993 is shown by a broken line and that in winter 1994 is shown by a solid line, based on data from the Japan Oceanographic Data Center.

edge to the Okinawa Trough region (Fig. 1). In terms of particle distribution in the East China Sea under the Marginal Sea Flux Experiment (MASFLEX) project, Hoshika et al. (1995) reported that a high concentration of suspended particles was found near the coastal region, with a maximum of about 30 mg l^{-1} in October 1993 and August 1994. In the Okinawa Trough, particles in the water column were transported laterally in deeper water (Yamada et al., 1995; Tanaka, 1997). These data suggest that settling of foraminifera in the water column may be influenced by multiple transport processes operating in the East China Sea.

Based on sediment trap samples collected at different depths in the North and Equatorial Pacific, seasonal variations in planktonic foraminiferal flux in deeper water were similar to those in shallower water (Thunell and Reynolds, 1984; Reynolds and Thunell, 1985). Thus, the planktonic foraminiferal tests were believed to settle mainly vertically in the open ocean. On the other hand, the flux of small particles increased with depth in the water column near the continental margin (Honjo et al., 1982). Resuspension is also active along the continental margin of the North Atlantic Ocean, resulting in the transport of phytoplankton cells and benthic and planktonic foraminiferal tests to offshore regions (Falkowski et al., 1994; Brunner and Biscaye, 1997). In some regions in the oceans the settling of planktonic foraminiferal tests cannot necessarily be attributed to vertical transport. Guptha et al. (1997), in their sediment traps study in the Bay

Table 1
Periods and sampling locations for stations located on the continental shelf to the shelf edge and in the Okinawa Trough

	Continental shelf to shelf edge			Okinawa Trough
Station	PN-12	PN-8	PN-5	SST2
Water depth	47 m	87 m	127 m	1070 m
Latitude	31°13′N	29°36′N	28°42′N	28°08′N
Longitude	123°06′E	125°07′E	126°26′E	127°11′E
Mooring depth	17 m 27 m	47 m 67 m	87 m 117 m	606 m 813 m 1019 m
Duration	1.04 day	1.91 day	1.90 day	15, 16 days
Dates	March 1–2, 1993	March 3–5, 1993	February 25–27, 1993	March 1–September 24, 1993
Mooring depth	19 m 29 m 39 m	33 m 73 m	45 m 85 m 115 m	606 m 813 m 1019 m
Duration	0.36 day	1.97 day	1.97 day	10 days
Dates	October 23, 1993	October 19–21, 1993	October 15–17, 1993	October 15 1993–February 22 1994

of Bengal, reported that the total foraminiferal flux increased with increasing depth in the water column, suggesting that lateral transport of foraminiferal tests affected the flux.

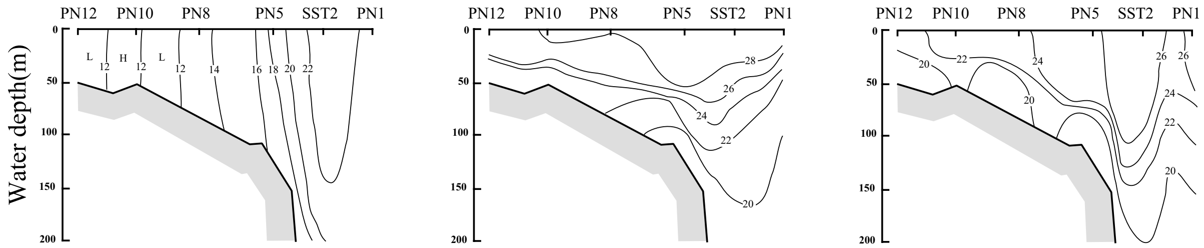
In this study, we used sediment trap samples for the East China Sea, and analyzed fluxes of planktonic foraminifera and their transport.

2. Materials and methods

Sediment trap samples were collected in the East China Sea. From the Okinawa Trough to the continental shelf (Fig. 1), time-series sediment traps, shaped like a funnel 50 cm in diameter (a 0.2-m^2 aperture) and covered by a baffle with a small grid, were deployed at three depths, i.e. 606, 813 and 1019 m (Fig. 1; Table 1) during two periods over the 337-day experiment. The first mooring consisted of 13 consecutive sample periods of 15–16 days each from 1 March to 24 September 1993, and the second mooring consisted of 13 consecutive sample periods of 10 days each from 15 October 1993 to 22 February 1994 (Table 2). Conventional cylindrical sediment traps, 17 cm in diameter (a 0.02-m^2 aperture) covered by a baffle with a small grid, were moored at three sites along a PN line (Fig. 1), from the continental shelf (Stations PN12 and PN8) to the shelf edge (Station PN5) in the East China Sea during the winter and autumn cruises of the R/V *Kaiyo* in 1993 (Fig. 1). The PN line is one of the observation transects of the Nagasaki Marine Observatory of the Japan Meteorological Agency in the East China Sea. In winter (25 February to

Table 2
Sampling periods for sediment traps deployed at the Okinawa Trough (Station SST2) in the East China Sea

	Dates	Duration
First period	March 1–16 1993	(15)
	March 16–April 1 1993	(16)
	April 1–17 1993	(16)
	April 17–May 3 1993	(16)
	May 3–19 1993	(16)
	May 19–June 4 1993	(16)
	June 4–20 1993	(16)
	June 20–July 6 1993	(16)
	July 6–22 1993	(16)
	July 22–August 7 1993	(16)
	August 7–23 1993	(16)
	August 23–September 8 1993	(16)
	September 8–24 1993	(16)
Second period	October 15–25 1993	(10)
	October 25–November 4 1993	(10)
	November 4–14 1993	(10)
	November 14–24 1993	(10)
	November 24–December 4 1993	(10)
	December 4–14 1993	(10)
	December 14–24 1993	(10)
	December 24 1993–January 3 1994	(10)
	January 3–13 1994	(10)
	January 13–23 1994	(10)
	January 23–February 2 1994	(10)
	February 2–12 1994	(10)
	February 12–22 1994	(10)



(a) Winter cruise(K92-09) (b) Summer cruise(K94-04) (c) Autumn cruise(K93-05)

Fig. 2. Temperature profiles along the PN line during (a) winter, (b) summer, and (c) autumn (after Hama et al., 1997).

3 March 1993), conventional sediment traps were deployed at 10 and 40 m above the seafloor for 1.9 days (Station PN5), and at 20 and 30 m above the bottom for 1.04 days (Station PN12). In autumn (15 October to 23 October 1993), the traps were deployed at 10, 40, and 80 m above the bottom for 1.97 days (Station PN5), at 30 and 50 m above the bottom for 11.97 days (Station PN8), and at 10, 20, and 30 m above the bottom for 0.36 days (Station PN12), as is shown in Table 1.

These conventional sediment trap samples were used to examine whether the flux in the continental shelf contributes to flux in the Okinawa Trough. Each sample cup was filled with filtered seawater containing 2% formalin before deployment. All the samples were stored at less than 3°C.

In the laboratory, all samples were sieved through a 1-mm screen, and then quantitatively split into aliquots using a precision rotary splitter (Honjo, 1978). We carried out the planktonic foraminiferal analysis on these aliquots for each sample. We stained 14 trap samples from three stations ranging in Stations PN12, PN8 and PN5 with rose Bengal to distinguish living specimens from dead ones (Walton, 1952). Each aliquot was then wet-sieved into four size fractions (less than 125 μm, 125–250 μm, 250–500 μm, and 500–1000 μm). All planktonic foraminifera larger than 125 μm were picked from the wet samples by using a small brush, and then identified and counted. Foraminiferal flux estimates were made in terms of the number of tests larger than 125 μm per square meter per day based on the sample split (1/8 or 1/16 in Station SST2, and 1/4 in Stations PN5, PN8 and PN12), the duration of sample collection, and the cross-sectional area (0.2 and 0.02 m^2) of the sediment trap.

3. Oceanographic setting

The East China Sea is located in the Asian monsoon zone. A cold northwesterly wind blows from Siberia to the Pacific Ocean across the Japanese Islands in winter. In contrast, a warm and humid southeasterly wind blows from the subtropical North Pacific high atmospheric pressure towards Asia in summer. The Kuroshio, a western boundary current of the subtropical gyre in the North Pacific, flows along the shelf edge to the Okinawa Trough area and then continues flowing northeastwards until it reaches the Pacific Ocean south of Kyushu.

The main stream of the Kuroshio across the PN line (Fig. 1) flows generally in a northeastern direction, following the shelf to the slope. Utilizing a towed Acoustic Doppler Current Profiler (ADCP) on 2–3 September 1991, Ito et al. (1995) reported that the Kuroshio flows northeast with a maximum velocity of 80.0 cm s^{-1} at 94 m depth, and progressively decreases with increasing depth at 100–600 m in the East China Sea. According to hydrographic data collected by the Japan Maritime Safety Agency during the experiment, the Kuroshi flowed offshore in summer 1993 and in winter 1994 (Fig. 1). In contrast, the Kuroshio flowed closer to the shelf edge in early spring and early autumn 1993.

Hydrographic data were collected at Station SST2 (or Station PN3, located just southwest of Station SST2) and at the PN line during the sediment trap experiment (Watanabe et al., 1995;

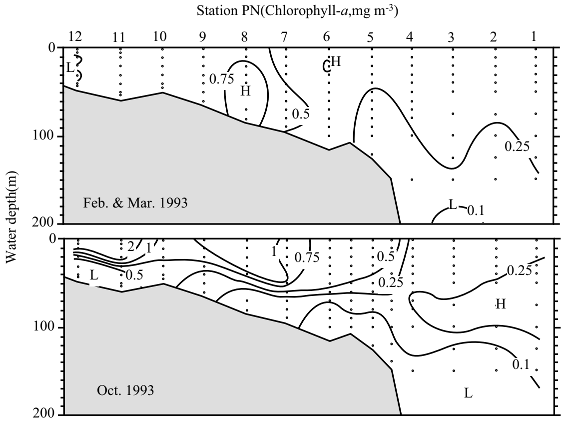


Fig. 3. Vertical profiles of chlorophyll-*a* along the PN line in winter (upper) and autumn (lower). 'H' refers to high concentrations of chl-*a* and 'L' refers to low concentrations (after Furuya et al., 1995).

Hama et al., 1997) and chlorophyll-*a* (chl-*a*) concentrations were obtained from Furuya et al. (1995) (Figs. 2 and 3). In late October 1993, the sea surface temperature in the Kuroshio was still higher than 26°C at Station PN3, whereas it had decreased to 25°C at the shelf edge (Station PN5) and had gradually decreased from the shelf edge (Stations PN8 and PN10) to the inner shelf area (Station PN12) (Fig. 2c). A distinct thermocline was present at 60–80 m depth from Stations PN5 to PN3 and tended to deepen toward Station PN3 (Station SST2). On the other hand, the thermocline became indistinct at the shelf stations. In late February/early March, sea surface temperature in the Kuroshio (Station SST2) was higher than 22°C even in winter, and a seasonal thermocline was present below 150 m depth (Fig. 2a). In summer, sea surface temperature increased to higher than 28°C from Stations PN1 to PN10 (Fig. 2b). Chl-*a* concentrations in the off-shelf area (Stations PN1–PN3) in October 1993 were low, ranging from 0.11 to 0.39 mg m^{-3}, and were medium at Station PN5 on the shelf edge, ranging from 0.30 to 0.57 mg m^{-3} (Fig. 3). Chl-*a* concentrations were higher than 1 mg m^{-3} at the shelf (PN8 and PN12). On the other hand, chl-*a* concentrations in March 1993 did not show any distinctive spatial variability through the PN line, and ranged from 0.44 to 0.70 mg m^{-3} in the surface layer. Chl-*a* was evenly distributed throughout the euphotic zone.

4. Results

4.1. Foraminiferal flux at the Okinawa Trough: Station SST2

The total foraminiferal flux was separated into three size fractions (Fig. 4a–c). The total foraminiferal flux for the size fraction of 125–250 μm varied from 114 to 993 tests m^{-2} day^{-1} in the shallow trap, from 100 to 3309 tests m^{-2} day^{-1} in the middle trap, and from 164 to 2977 tests m^{-2} day^{-1} in the deep trap (Fig. 4a). The maximum flux for this size fraction was about twice as high in the middle and deep traps as in the shallow one. The total foraminiferal flux for the size fraction of 250–500 μm varied from 18 to 489 tests m^{-2} day^{-1} in the shallow trap, from 8 to 427 tests m^{-2} day^{-1} in the middle trap, and from 35 to 503 tests m^{-2} day^{-1} in the deep trap (Fig. 4b). The total foraminiferal flux for the size fraction of 500–1000 μm varied from 4 to 214 tests m^{-2} day^{-1} in the shallow trap, from 5 to 58 tests m^{-2} day^{-1} in the middle trap, and from 4 to 62 tests m^{-2} day^{-1} in the deep trap (Fig. 4c). Thus, the apparent increase in total foraminiferal flux with increasing depth largely occurred in the 125–250-μm size fraction. With regard to the total flux of three size fractions, the peaks were seen in January to February at all three depths, and they were more prominent at the middle and the deep traps.

We identified a total of 34 species of planktonic foraminifera in the East China Sea sediment traps. There were 6 species with characteristic seasonal flux patterns; i.e. *Globigerina bulloides* d'Orbigny, *Globigerinita glutinata* (Egger), *Globigerinoides ruber* (d'Orbigny), *Globigerinoides sacculifer* (Brady), *Neogloboquadrina dutertrei* (d'Orbigny), and *Pulleniatina obliquiloculata* (Parker and Jones). These six species accounted for 69.1% of the total foraminiferal flux in the shallow trap, 74.7% in the middle trap, and 75.6% in the deep trap. Temporal distribution patterns for all the above species are shown in Figs. 5 and 6. Due

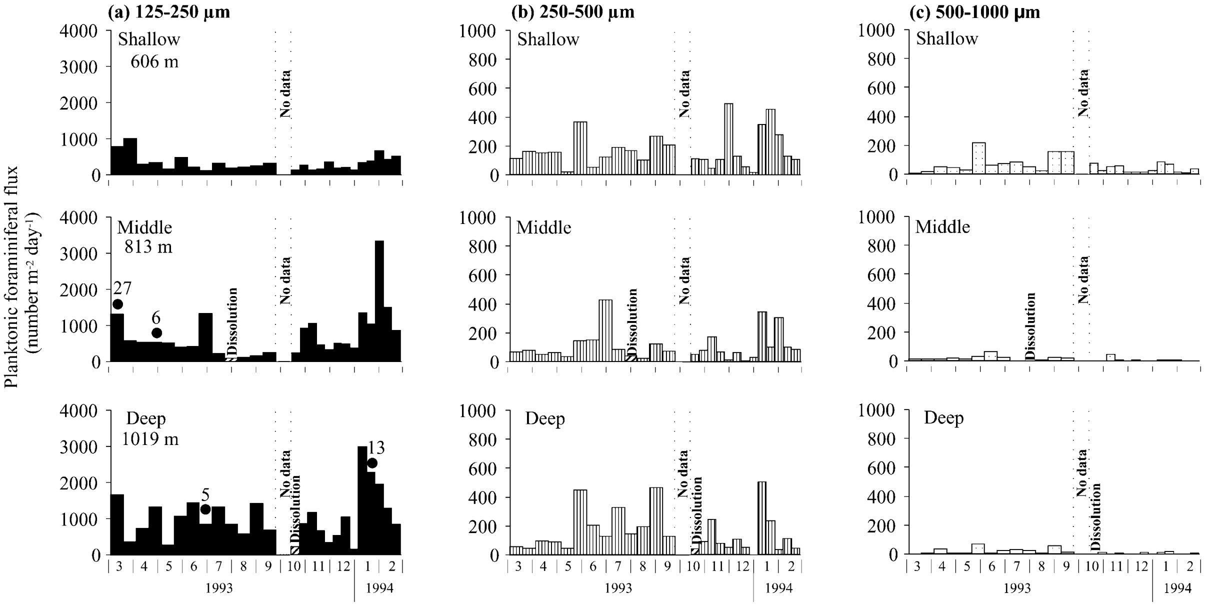


Fig. 4. Total planktonic foraminiferal flux in the Okinawa Trough. The flux for each period was divided into three size fractions: (a) 125–250 μm; (b) 250–500 μm; and (c) 500–1000 μm. Note the different vertical scales. The width of each bar indicates the collection duration. The periods with benthic foraminiferal flux are indicated by closed circles with the flux values noted. The bars with slanted lines indicate the period was influenced by carbonate dissolution in the sediment trap (see text).

to their sparse occurrence, the remaining 28 species are neither shown nor discussed.

Among the six species, *Globigerina bulloides* and *Globigerinita glutinata* were the most abundant throughout the period of sample collection, accounting for 22% and 20%, respectively, of the total planktonic foraminiferal flux at the Okinawa Trough. Both of these species occurred in abundance mostly in the smaller size fraction of 125–250 μm in all the traps during January through February. Fluxes of these species in the middle and deep traps showed increases by factors of 2 and 3 times, respectively, greater than those in the shallow trap (Fig. 5a,b).

Maximum fluxes of *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* occurred during the period from January to February at all three depths, and increased with increasing depth (Fig. 6a,b). These two species were mainly found in the size fraction of 250–500 μm in the shallow trap, while they were found abundantly in the size fraction of 125–250 μm in the two deeper traps.

Globigerinoides ruber and *Globigerinoides sacculifer* were observed abundantly in the size fraction of 250–500 μm from July through November in the shallow trap (Fig. 6c,d). The temporal variation for the size of *G. ruber*, which was larger in summer and smaller in winter, was consistent with that of the trap reported by Deuser et al. (1981) in the Sargasso Sea. In the two deeper traps, these two species were found abundantly in the size fraction of 125–250 μm.

In terms of seasonal variations in planktonic foraminiferal flux in the shallow trap, the flux maxima for the two dominant species, *Globigerina bulloides* and *Globigerinita glutinata*, associated with *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata*, were observed in winter. On the other hand, the fluxes in summer through autumn were characterized by abundant occurrences of two other species, *Globigerinoides ruber* and *Globigerinoides sacculifer*. Fluxes of these species increased with increasing depth, and the smaller size fraction for each species was observed more abundantly in the two deeper traps than in the shallow trap.

A few benthic foraminiferal tests in the size range of 125–250 μm were present in the middle

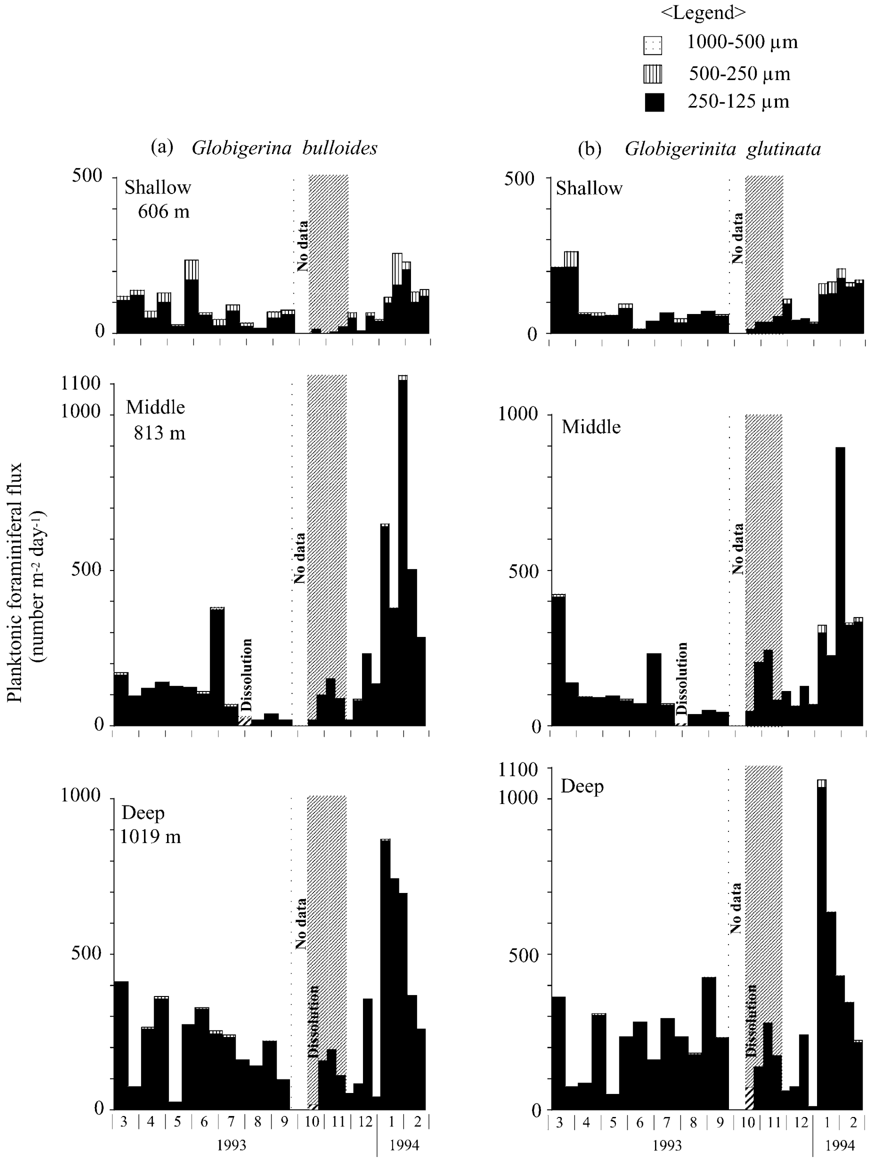
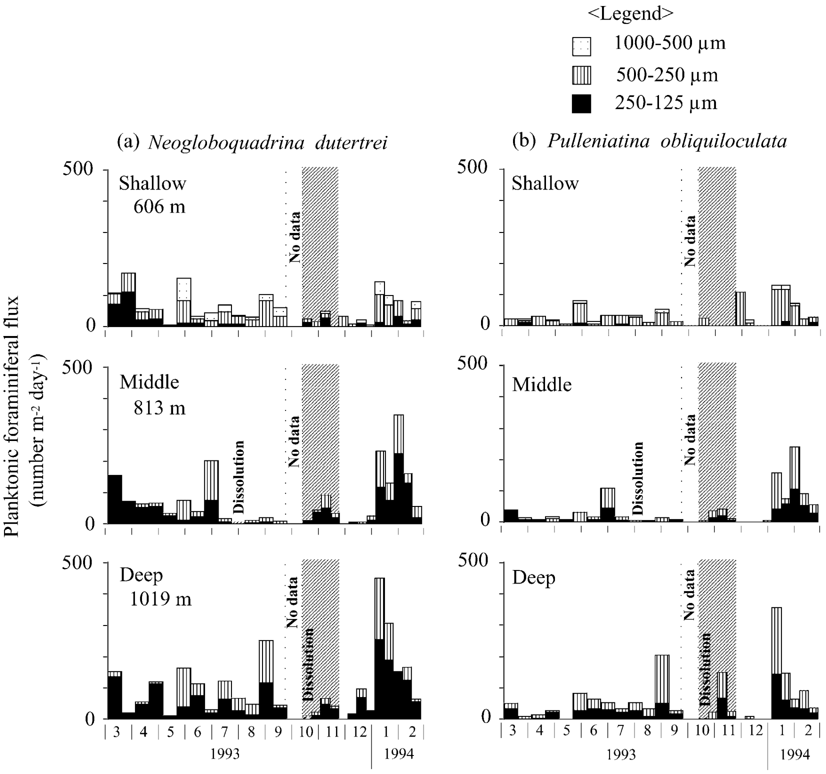


Fig. 5. Fluxes for: (a) *Globigerina bulloides* and (b) *Globigerinita glutinata* at Okinawa Trough for the shallow, middle, and deep traps. The shaded areas denote the time period that can be compared to the species composition of the flux at Stations PN5 and SST2 (see text).

and deep traps (Fig. 4a). The 19 specimens actually counted belonged to 16 species. The benthic foraminiferal flux varied from 5 to 27 tests m^{-2} day^{-1}, being very low compared to that for planktonic foraminifera. The occurrence of these benthic foraminifera suggests the prevalence of resuspension on the seafloor. Most of the benthic foraminiferal species encountered in the deeper traps at the Okinawa Trough are commonly found on the inner to the outer shelf region (Inoue, 1989; Akimoto, 1990), such as *Trochammina nitida* Brady, *Bolivina decussata* Brady, *Hauerinella tumidulum* (Brady), *Miliolinella australis* (Parr), *Miliolinella oblonga* (Montagu), *Cibicidoides wuel-*


(a) *Neogloboquadrina dutertrei*

(b) *Pulleniatina obliquiloculata*

(c) *Globigerinoides ruber*

(d) *Globigerinoides sacculifer*

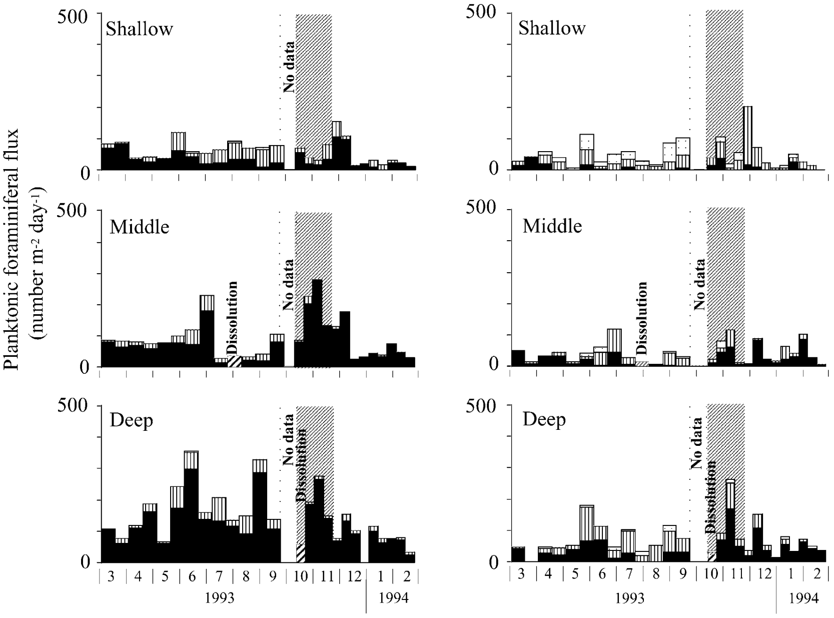


Fig. 6. Fluxes for: (a) *Neogloboquadrina dutertrei*; (b) *Pulleniatina obliquiloculata*; (c) *Globigerinoides ruber*; and (d) *Globigerinoides sacculifer* at the Okinawa Trough. The shaded areas denote the period for comparing to the species composition between the flux at Stations PN5 and SST2 (see text).

Table 3a
Actually counted numbers of foraminifera in the conventional traps (Stations PN5, PN8 and PN12) along the PN line from the inner shelf to the shelf edge in winter and autumn 1993

	Trap station	Duration (days)	Water depth (m)	Planktonic foraminifera well preserved Stained (tests)	Planktonic foraminifera well preserved Non-stained (tests)	Planktonic foraminifera poorly preserved (tests)	Benthic foraminifera (tests)
Late winter, 1993	PN5	1.9	87	9	0	1	0
			117	19	8	56	102
	PN8	1.91	47	0	0	2	1
			67	0	0	4	8
	PN12	1.04	17	0	0	0	1
			27	0	0	1	6
Late October, 1993	PN5	1.97	45	109	15	0	0
			85	51	19	31	29
			115	49	125	1099	467
	PN8	1.97	33	0	3	0	0
			53	0	2	1	5
	PN12	0.362	19	0	0	0	0
			29	0	0	0	0
			39	0	0	2	3

A quarter aliquot of each trap sample was used for foraminiferal analysis.

lerstorfi (Schwager), *Discorbinella convexa* (Takayanagi), *Paracassidulina quasicarinata* Nomura, and *Uvigerina proboscidea* Schwager.

4.2. Foraminiferal flux at the continental shelf to the shelf edge: Stations PN5, PN8 and PN12

The planktonic foraminiferal specimens collected at three stations on the continental shelf were divided into two groups based on their degree of preservation (Table 3a). One group contained specimens for which the test structure was well preserved. Specimens with spines remaining intact were present in spinose species, belonging to *Globigerinoides* and *Globigerina*. Moreover, we divided these forms into two groups, i.e. one stained and another one which did not stain after treatment with rose Bengal. The second group had specimens with primary apertures or sutures that were filled with mud and adherent particles. These specimens were sometimes partly broken.

Benthic foraminiferal specimens were present in traps placed at 10 m above the seafloor as shown in Table 3a. The most abundant flux occurred at Station PN5 at 115 m depth (10 m above bottom (ab)) in late October, and the second biggest flux occurred in late February 1993. They were also present at 30 m ab at Stations PN12 and PN8 in March, at Station PN8 in October 1993, and at 40 m ab at Station PN5 in October 1993. All the specimens of benthic foraminifera were found in the 125–250-μm size fraction except for the sample at Station PN5 at 115 m in late October. These results indicate that marked resuspension of surface sediments occurred on the continental shelf to the shelf edge region. The foraminiferal fluxes were higher at the shelf edge than at the inner shelf, and larger during late October than during late February/early March.

Species fluxes at Station PN5 of well-preserved planktonic foraminifera with both stained and non-stained tests were present in relatively large quantities in the shallow trap (Table 3b). *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata*, which were present in the highest abundance among the well-preserved planktonic foraminifera, constituted 20% and 15%, respectively, of the total well-preserved planktonic foraminifera in all three traps, with secondary peak abundances of *Globigerina bulloides*, *Globigerinita glutinata*, *Globorotalia anfracta*, *Globigerinoides ruber*, and *Globigerinoides sacculifer*, which together

Table 3b
Actually counted numbers of planktonic foraminifera at the shelf edge (Station PN5) in autumn 1993

Species	Mooring depth								
	45 m			85 m			115 m		
	Well-preserved tests		Poorly preserved tests	Well-preserved tests		Poorly preserved tests	Well-preserved tests		Poorly preserved tests
	Stained	Non-stained		Stained	Non-stained		Stained	Non-stained	
Globigerina bulloides	6	0	0	10	1	7	15	16	314
G. falconensis	0	0	0	0	0	0	0	5	28
G. quinqueloba	0	0	0	0	0	0	0	2	9
G. rubescens	1	0	0	0	0	1	0	0	28
Globigerinella aequilateralis	1	0	0	0	0	0	1	0	1
G. calida	1	0	0	0	1	0	0	2	38
Globigerinita glutinata	1	0	0	0	2	8	11	25	305
Globigerinoides conglobatus	1	0	0	0	0	0	5	1	14
G. ruber	5	3	0	2	2	2	3	19	139
G. sacculifer	11	1	0	9	0	0	3	5	23
G. tenellus	3	0	0	2	0	1	2	3	16
Globorotalia anfracta	0	0	0	1	3	2	1	33	7
G. bermudezi	0	0	0	0	0	0	0	0	1
G. inflata	0	0	0	0	0	0	0	0	1
Neogloboquadrina dutertrei	43	0	0	21	9	10	2	3	104
Pulleniatina obliquiloculata	36	11	0	6	1	0	3	1	58
Tenuitella fleisheri	0	0	0	0	0	0	3	8	10
T. parkerae	0	0	0	0	0	0	0	2	1
T. sp.	0	0	0	0	0	0	0	0	0
Turborotalita humilis	0	0	0	0	0	0	0	0	2
TOTAL	109	15	0	51	19	31	49	125	1099

A quarter aliquot of each trap sample was used for foraminiferal analysis.

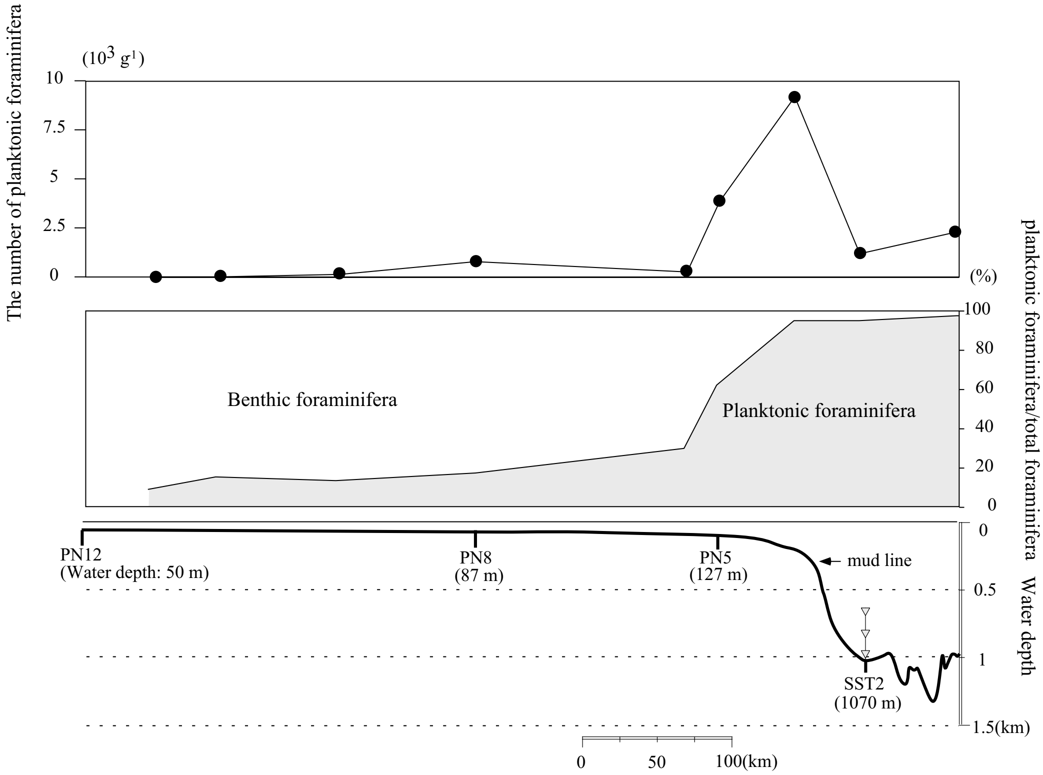


Fig. 7. The number of planktonic foraminifera per gram and the ratio of planktonic foraminifera to total foraminifera in the surface sediments along the PN line on the basis of data from Xu and Oda (1999). The arrow shows the mud line.

constituted 42% of the total well-preserved tests at Station PN5. A similar trend also occurred among the stained forms. Among the stained planktonic foraminifera, *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* were abundant in the two shallower traps at 45 and 85 m, associated with *G. bulloides*, *G. ruber*, and *G. sacculifer*. On the other hand, *G. glutinata* was common in the deep trap at 115 m, associated with *G. bulloides*.

5. Discussion

5.1. Different transport processes at the continental shelf and the Okinawa Trough

In the East China Sea, benthic and planktonic foraminifera occurred in traps at 10–40 m ab at Stations PN5–PN12 located at sites on the continental shelf to the shelf edge. Specimens of planktonic foraminifera in these traps were generally filled with mud.

The number of planktonic foraminifera per gram in the surface sediments along the PN11–PN5 transect showed an increase from the inner shelf toward the shelf edge (Fig. 7). This trend was consistent with the flux in traps taken above the seafloor, generally increasing from the inner shelf at PN12 toward the shelf edge at PN5. The surface sediments on the inner shelf (PN12; 50 m water depth) to the shelf edge (PN5; 127 m water depth) are composed of sand, while they are composed of mud on the upper slope to the Okinawa Trough (Oguri et al., 1997). The most abundant planktonic foraminifera per gram occurred on the uppermost part of the continental slope at about 300 m water depth, which is close to the mud line in the East China Sea (Fig. 7). Furthermore, values of the P/T ratio (planktonic foraminifera/total foraminifera) in the surface sediments along the

PN line also indicated an increase from the inner shelf (8.8% at Station PN11) toward the shelf edge (61.7% at Station PN5). The P/T ratio on the basis of benthic foraminifera and poorly preserved planktonic foraminifera in a trap sample at Station PN5 at 115 m (10 m ab) in October, when foraminifera were most abundant, was 70.2%, which was similar to that for the surface sediment at Station PN5. *Globigerina bulloides* and *Globigerinita glutinata* occurred in the greatest abundance within the poorly preserved planktonic foraminifera in the deep trap, constituting 28% each; these values were also similar to those for the species in surface sediment at Station PN5 (Fig. 8). The flux of benthic and poorly preserved planktonic foraminifera reflected that of the surface sediments due to resuspension from the seafloor on the continental shelf to the shelf edge. Moreover, in trap samples taken from 45, 85 and 115 m at Station PN5 in October, the percentage of well-preserved specimens relative to total planktonic foraminifera (poor+well preserved) reached about 100%, 70% and 14%, respectively. Thus, the influence of resuspension decreased from the deep to the middle traps, and was not seen in the shallow trap at 45 m.

At the Okinawa Trough, planktonic foraminiferal flux increased with increasing depth, associated with a few benthic foraminiferal specimens in the two deeper traps. Since the occurrence of benthic foraminifera in sediment traps originated from resuspension, the increased planktonic foraminiferal flux in the two deeper traps at the Okinawa Trough probably was due to resuspended specimens transported by lateral currents from the shelf to the slope as well. Tanaka (1997) reported that the total fluxes of coccoliths in the same sediment trap samples increased by factor 3 and 10 in the middle and deep traps, respectively. He further attributed these increases to the lateral transport of particles from the adjacent shelf edge and slope to the central part of the Okinawa Trough, particularly during mid-autumn through spring. Yamada et al. (1995) also analyzed the same trap samples at Station SST2 for the concentration of ^{210}Pb, and suggested that settling particles in the lower trap were supplied mainly by lateral transport in spring and/or winter. Increased particle flux with increasing depth in the water column is not common in sediment trap experiments. Honjo et al. (1982), in their sediment trap study in the Panama Basin, suggested that the flux of lithogenic particles increased with increasing depth, primarily due to the presence of clay in the bottom sediment on the continental slope associated with a change of current direction. On the eastern margin of North America, phytoplankton cells were transported laterally toward the offshore (Falkowski et al., 1994). The foraminiferal flux, however, changes little with increasing depth in the open ocean (Thunell and Honjo, 1981; Thunell et al., 1983;

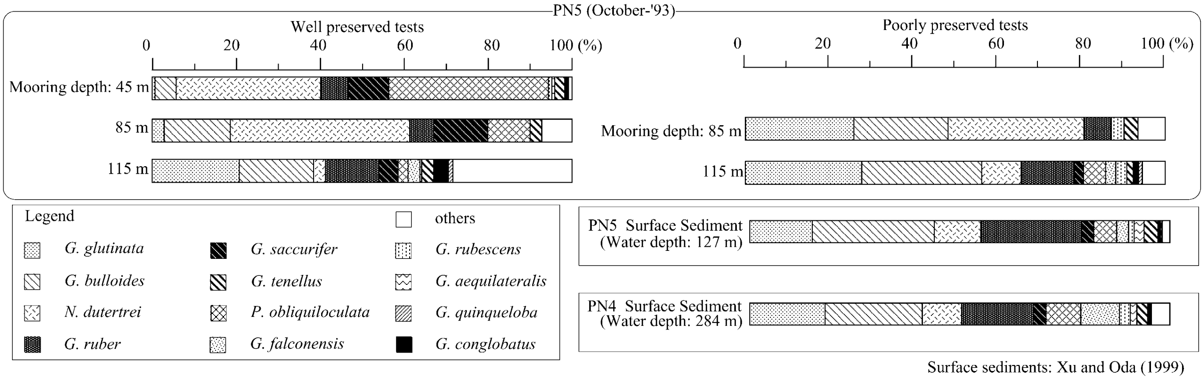


Fig. 8. Comparison of relative abundances of the 12 major planktonic foraminiferal species as indicated by the flux from the conventional sediment trap samples taken at the shelf edge at Station PN5 in October 1993 and surface sediments at Stations PN5 and PN4. Planktonic foraminiferal specimens from the conventional trap samples are divided into two groups: well-preserved specimens, including stained and non-stained forms, and poorly preserved ones that were filled with mud.

Reynolds and Thunell, 1985). On the other hand, some reports stated that the foraminiferal flux increased with increasing depth. Brunner and Biscaye (1997) also suggested that large quantities of benthic and planktonic foraminifera with a median in the size class of 98–114 μm and terrigenous materials were delivered to the upper slope by seaward, midwater advection during annual storms. In the Bay of Bengal, foraminiferal flux significantly increased with increasing depth related to the monsoon (Guptha et al., 1997); that is, the maximum planktonic foraminiferal fluxes in all size fractions from 150 to 1000 μm in the deep trap deployed at 2168 m water depth were twice those in the shallow trap at 950 m water depth, suggesting that the flux was affected by lateral transport. At the Okinawa Trough, the total fluxes were 1.5 times higher in the middle trap and 2.2 times higher in the deep trap than in the shallow one, largely in the smaller size fraction of 125–250 μm (Fig. 4a). The foraminiferal tests in the two deeper traps were inferred to have been transported laterally. However, planktonic foraminiferal tests filled with mud as observed in traps on the shelf to the shelf edge were not found in all three traps at the Okinawa Trough. Therefore, the planktonic foraminifera do not originate from the sediments of the continental shelf, and they are likely to be carried away by lateral movements during settling. Most planktonic foraminifera live in the euphotic zone (Bé, 1977), and their tests sink freely as individual tests or attached to organic aggregates through the water column in the size fraction greater than 125 μm. The sinking speed for individual planktonic foraminifera depends on their test weight and the presence or absence of spines (Takahashi and Bé, 1984). Assuming a sinking speed of 150–1300 m day^{-1} from their experiments, the planktonic foraminiferal tests at the Okinawa Trough were expected to arrive at the middle and deep traps from the surface water with maximum time lags of 5.3 and 6.6 days. The planktonic foraminiferal tests are assumed to have been transported laterally during these periods. Although we have no current data for the time during the trap experiments, the currents are variable around the continental slope (Sugimoto et al., 1988; Ito et al., 1995; Yanagi et al., 1998). The meander of the Kuroshio front on the continental shelf occurs with the changes of current directly (Sugimoto et al., 1988; Yanagi et al., 1998). Ito et al. (1995) observed a current speed of 10 cm s^{-1} which sloped down to the Okinawa Trough. This current may help the foraminifera to transport laterally.

The foraminiferal flux for the size fraction of 500–1000 μm decreased with increasing depth although those for the other two size fractions did not increase with depth (Fig. 4c). The current velocity around traps is one of the reasons for changing the trapping efficiency of sediment traps (Gardner, 1980), and the particles of larger size make up an increasingly larger fraction of the total flux as current speed increases (Baker et al., 1988). At Station SST2, the Kuroshio had a speed of < 20 cm s^{-1} at the depth of the shallow trap (Ito et al., 1995; Kaneko et al., 1993), and very weak currents with average speeds of 3.0 and 4.7 cm s^{-1} occurred during the month-long experiment at 775 m water depth (Sugimoto et al., 1988). These differences of current velocities between shallow and deep water depth may cause a decrease with increasing depth for the foraminiferal flux of the larger size fraction. However, as the decreasing foraminiferal flux for the 500–1000-μm size fraction was smaller than the flux for the other two size fractions, the trapping efficiency of the sediment trap had little effect on our system.

5.2. *Source of particles being laterally transported to the Okinawa Trough in early autumn*

Comparison of flux results for Stations PN5 and SST2 in early autumn gives us a clue as to where the particles in the Okinawa Trough came from. In Station PN5, as the traps were deployed at the depth of 45–115 m within the depth range of planktonic foraminifera dwelling, some planktonic foraminifera apparently were captured by the trap while they were alive. As the conventional trap in the continental shelf collected not only dead specimens but also living specimens, some of the stained specimens may represent the living population. We observed mainly six species at Station PN5 in late October 1993. Stained specimens of *Neogloboquadrina dutertrei* were abun-

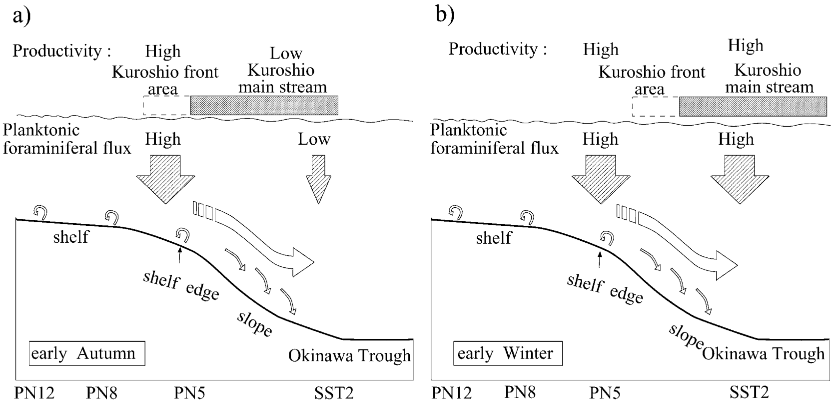


Fig. 9. Schematic illustration of potential vertical and advectional transport of planktonic foraminifera through the water column from the surficial source area to the traps at the Okinawa Trough in: (a) early autumn, and (b) early winter, explaining the increased fluxes with increasing depth in the sediment traps at the Okinawa Trough.

dant within and above the thermocline, associated with those of *Pulleniatina obliquiloculata* and *Globigerina bulloides*. On the other hand, stained specimens of *Globigerinita glutinata* were common below the thermocline, associated with that of *G. bulloides* (Table 3b). These stained species are considered to reflect the population at the Kuroshio front, because Station PN5 was situated on the Kuroshio front in October (Fig. 1). At the Okinawa Trough during late October/early November, the middle and deep traps were characterized by peak fluxes, although the fluxes at the shallow trap were very low (Figs. 5 and 6, shaded area). The peak fluxes in both the middle and deep traps were characterized by the occurrence of *G. bulloides*, *G. glutinata*, *Globigerinoides ruber*, *Globigerinoides sacculifer*, *N. dutertrei*, and *Pulleniatina obliquiloculata*, which constituted 75–87% of the total flux during autumn, whereas the fluxes of these six species in the shallow trap at the Okinawa Trough were very low, particularly *G. bulloides*, *G. glutinata* and *P. obliquiloculata* (Figs. 5 and 6, shaded area). Since the planktonic foraminiferal flux in the shallow trap at the Okinawa Trough reflected populations of the mixed layer in the photic zone of the main stream of the Kuroshio, the increases in flux of these six species in the middle and deep traps implied that a significant portion of flux seemed to have arrived at the two deeper traps through lateral transport during settling (Fig. 9a).

In the Panama Basin, *Neogloboquadrina dutertrei* was observed abundantly within the thermocline (Fairbanks et al., 1982). The isotope studies of Curry et al. (1983) indicated that as the thermocline shoaled, *N. dutertrei* adjusted its habitat depth in order to remain within a preferred temperature range. Thunell and Reynolds (1984) also observed that the production rate of *N. dutertrei* increased substantially as the thermocline shoaled and upwelling became extensive from February through April in the Panama Basin. These findings are consistent with those of previous ecological studies in both the Pacific (Bradshaw, 1959) and Atlantic (Bé and Tolderlund, 1971), which indicated that *N. dutertrei* is generally most abundant in upwelling regions or marginal areas of high productivity. Furthermore, the gyre margin of the Kuroshio was characterized by *N. dutertrei* associated with *Pulleniatina obliquiloculata* in the surface sediments off southwest Japan and in the East China Sea (Takemoto and Oda, 1997; Xu and Oda, 1999). Stained *N. dutertrei* at Station PN5 was abundant within and above the thermocline, associated with *P. obliquiloculata*, and there were higher values of chl-*a* (0.30–0.57 mg m^{-3}) than at Station SST2 (0.11–0.39 mg m^{-3}) (Hama et al., 1997). These results are consistent with those of previous studies. Thus, the oceanographic conditions at the Kuroshio front at Station PN5 in October seemed to be optimal for the production of *N. dutertrei* and *P. obliquiloculata*.

Although *Globigerina bulloides* is generally considered to be a subpolar form (Bé, 1977), it is also present in tropical upwelling regions (Duplessy et al., 1981). It is dominant during the southwest monsoon in the Arabian Sea (Curry et al., 1992). In the Panama Basin, Thunell and Reynolds (1984) reported that fluxes of *G. bulloides* were relatively high throughout the year, with increased production occurring during the summer phytoplankton bloom when the surface mixed layer was relatively deep, and in association with the increased upwelling and enhanced primary productivity during the February–March period. Bradshaw (1959) and Bé and Tolderlund (1971) suggested that *Globigerinita glutinata* was 'eurythermal', with a preference for tropical and subtropical waters. In their study of the Panama Basin, Thunell and Reynolds (1984) concluded that *G. glutinata* clearly preferred warmer water environments, though it could also thrive in the nutrient-rich waters owing to upwelling. In samples taken at Station PN5 in October, stained forms of both *G. bulloides* and *G. glutinata* were common in the surface mixed layer, where the temperature was 24–25°C and the depth-integrated values of chl-*a* were relatively high. These results are consistent with those of previous studies, although stained specimens of *G. glutinata* were commonly found from the base to below the thermocline in the lower trap at Station PN5.

Globigerinoides sacculifer, along with *Globigerinoides ruber*, is generally the most abundant species in the equatorial regions of the Atlantic, Indian, and Pacific oceans (Bradshaw, 1959; Bé and Tolderlund, 1971), preferring surface water temperatures higher than 24°C. In the Panama Basin, *G. sacculifer* and *G. ruber* were most common in the warm mixed layer above the thermocline on the plankton tow material (Fairbanks et al., 1982). In fact, stained *G. ruber* and *G. sacculifer* were most common in the surface mixed layer above the thermocline in October at Station PN5, where the surface temperature was 25°C. Thus, planktonic foraminifera at Station PN5 in October were characterized not only by the six stained species *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata*, *Globigerina bulloides*, *Globigerinita glutinata*, *G. sacculifer* and *G. ruber*, but also by well-preserved non-stained forms (Table 3b). The Kuroshio frontal conditions seemed to be suitable for the production of herbivorous species such as *G. bulloides*, *G. glutinata*, *N. dutertrei* and *P. obliquiloculata*. Depth-integrated values of chl-*a* at Station PN5 were higher than those at the Okinawa Trough in the main stream of the Kuroshio, so that the fluxes of these species in the shallow trap at the Okinawa Trough were very low during autumn. The fluxes of *G. ruber* and *G. sacculifer* were higher than those of *N. dutertrei* and *P. obliquiloculata* at the two deeper traps in the Okinawa Trough although those fluxes were relatively low in the trap at Station PN5 in late October. However, the water temperature was still high (more than 24°C) from the shelf edge to the Okinawa Trough in autumn (Fig. 2c). Thus, water conditions seemed to be suitable for the production of *G. ruber* and *G. sacculifer* in a wide area from the shelf edge to the Okinawa Trough. Consequently, the fluxes of *G. ruber* and *G. sacculifer* may increase by lateral transportation.

5.3. Flux maximum in winter–early spring at the Okinawa Trough

We found flux peaks at the Okinawa Trough during January through February at all three depths; however, this tendency was more prominent at the middle and deep traps. In the shallow trap, generally the fluxes of both *Globigerina bulloides* and *Globigerinita glutinata* were distinctively high, associated with *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata*, in winter when well-mixed surface water with a relatively deep thermocline was prevalent.

Sea surface temperatures in the Kuroshio at the Okinawa Trough were greater than 22°C and a seasonal thermocline was present below 150 m water depth during a winter cruise in March 1993. Chl-*a* was evenly distributed throughout the euphotic zone, and depth-integrated values of chl-a between Stations PN5 and SST2 ranged from 22 to 36 mg m^{-3} (Hama et al., 1997). The depth-integrated chl-*a* peaked during January through February at the offshore regions of the East China Sea during 1973–1984 (Imai et al., 1988). Chl-*a* peaks in winter conditions in both the main stream and front area of the Kuroshio due to active vertical circulation with a relatively deep thermocline and a temperature of 22–23°C induced mainly by the monsoon wind. Thus, conditions at both stations seemed to be optimal for production of herbivorous species such as *Globigerina bulloides*, *Globigerinita glutinata*, *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata* in winter.

The maximum peaks for the species in all three traps at the Okinawa Trough in winter were caused by processes of both vertical and lateral transport. The distinctive flux peak at the shallow trap was induced mainly by vertical transport from areas where four species grew abundantly in the main stream of the Kuroshio, which flows farther off the shelf edge. In contrast, significantly extra planktonic foraminifera in the two deeper traps were inferred to have originated from lateral transport from areas of prevailing high productivity of the four species in the Kuroshio front area (Fig. 9b).

Thus, temporal variations in the flux patterns observed in the three traps at the Okinawa Trough were in response to seasonal variations in hydrographic conditions. The flux patterns for planktonic foraminifera at the three depths at Station SST2, deployed under the main stream of the Kuroshio, were most likely regulated by the productivity of the surficial source areas, probably related to the fluctuation of the axis of the Kuroshio. Size distribution patterns at the three depths may have depended on the distance between the traps and the source area during lateral transport. This could partially explain the source of the foraminiferal flux. There may also be multiple sources since there was no explanation for the excess foraminiferal flux of some species at the deeper trap (e.g. *Globigerinoides ruber* and *Globigerinoides sacculifer* in late October). To address this problem, we need to analyze the fluxes not only around the shelf edge but also in a wide area including the eastern part of the Okinawa Trough.

6. Conclusions

Analysis of the planktonic foraminiferal flux into sediment traps placed at points from the continental shelf to the central Okinawa Trough revealed lateral transport processes.

(1) On the continental shelf to the shelf edge, we observed high benthic foraminiferal flux during late October and late February. These results suggest that significant resuspension of surface sediments occurred at those times.

(2) In the sediment traps placed at the Okinawa Trough, the planktonic foraminiferal flux increased with depth. The amount of flux of planktonic foraminifera in the deeper traps beyond that to the surface trap most likely originated from lateral transport of suspended particles in the water column.

(3) We found *Neogloboquadrina dutertrei* in abundance above the thermocline at the shelf edge in early autumn, associated with *Pulleniatina obliquiloculata* and *Globigerina bulloides* as well as with *Globigerinoides ruber* and *Globigerinoides sacculifer*. On the other hand, *Globigerinita glutinata* was common below the thermocline, associated with *G. bulloides*. The species that were found within and above the thermocline at the shelf edge seem to have arrived at the deeper water in the Okinawa Trough through lateral transport.

(4) *Globigerina bulloides* and *Globigerinita glutinata* generally showed distinctively high fluxes at the Okinawa Trough in early winter, associated with *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata*. During this season, hydrographic conditions from the shelf edge to the Okinawa Trough seem to have been optimal for the production of these four species. Consequently, the significantly extra planktonic foraminiferal flux in the deeper water at the Okinawa Trough is believed to have originated from lateral transport from areas of prevailing high productivities of the four species.

Acknowledgements

We thank the MASFLEX group and the officers and crew of R/V *Kaiyo* of the Japan Marine Science and Technology Center for their shipboard work. We are grateful to Dr. Y. Tanaka of the National Institute of Advanced Industrial Science and Technology for providing the sediment trap samples. We would like to express our sincere appreciation to Dr. M.V.S. Guptha of the National Institute of Oceanography, India, for constructive comments and suggestions that improved the manuscript. We thank Dr. X. Xu of the Japan Marine Science and Technology Center and Dr. K. Akimoto of Kumamoto University for reading the manuscript and for comments on benthic foraminifera. We also thank Dr. Y. Takayanagi, Professor Emeritus of Tohoku University for reading the manuscript. Finally, we thank Dr. S. Tsunogai, Professor Emeritus of Hokkaido University, Dr. K. Iseki of the National Research Institute of Fisheries and Environment of Inland Sea, Dr. Y. Saito of the National Institute of Advanced Industrial Science and Technology, and Dr. M. Kusakabe of the Japan Marine Science and Technology Center, for providing the opportunity to write this paper and for providing valuable data collected during the MASFLEX project. This research was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan (No. 08404030), to M.O.

References

Akimoto, K., 1990. Distribution of Recent benthic foraminiferal faunas in the Pacific off Southwest Japan and around Hachijojima Island. Sci. Rep. Tohoku Univ. (Geol.) 60, 139–233.

Baker, E.T., Milburn, H.B., Tennant, D.A., 1988. Field assessment of sediment trap efficiency under varying flow conditions. J. Mar. Res. 46, 573–592.

Bé, A.W.H., 1977. An ecological, zoogeographic and taxonomic review of recent planktic foraminifera. In: Ramsay, A.T.S. (Ed.), Oceanic Micropalaeontology, vol 1. Academic Press, London, pp. 1–100.

Bé, A.W.H., Tolderlund, D.S., 1971. Distribution and ecology of living planktic foraminifera in surface waters of the Atlantic and Indian Oceans. In: Funnel, B.M., Riedel, W.R. (Eds.), The Micropaleontology of the Oceans. Cambridge University Press, Cambridge, pp. 105–149.

Bradshaw, J.S., 1959. Ecology of living planktic foraminifera in the North and Equatorial Pacific Ocean. Contrib. Cushman Found. Foraminif. Res. 10, 25–64.

Brunner, C.A., Biscaye, P.E., 1997. Storm-driven transport of foraminifers from the shelf to the upper slope, southern Middle Atlantic Bight. Cont. Shelf Res. 17, 491–508.

Curry, W.B., Thunell, R.C., Honjo, S., 1983. Seasonal changes in the isotopic composition of planktic foraminifera collected in Panama Basin sediment traps. Earth Planet. Sci. Lett. 64, 33–43.

Curry, W.B., Ostermann, D.R., Guptha, M.V.S., Ittekkot, V., 1992. Foraminiferal production and monsoonal upwelling in the Arabian Sea: Evidence from sediment traps. In: Summerhayes, C.P., Prell, W.L., Emeis, K.C. (Eds.), Upwelling Systems: Evolution since the Early Miocene. The Geological Society of London, pp. 93–106.

Deuser, W.G., Ross, E.H., Hemleben, C., Spindler, M., 1981. Seasonal changes in species composition, numbers, mass, size, and isotopic composition of planktic foraminifera settling into the deep Sargasso Sea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 33, 103–127.

Duplessy, J.C., Bé, A.W.H., Blanc, P.L., 1981. Oxygen and carbon isotopic composition and biogeographic distribution of planktic foraminifera in the Indian Ocean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 33, 9–46.

Fairbanks, R.G., Sverdlove, M., Free, R., Wiebe, P.H., Bé, A.W.H., 1982. Vertical distribution and isotopic fractionation of living planktic foraminifera from the Panama Basin. Nature 298, 841–844.

Falkowski, P.G., Biscaye, P.E., Sancetta, C., 1994. The lateral flux of biogenic particles from the eastern North American continental margin to the North Atlantic Ocean. Deep-Sea Res. II 41, 583–601.

Furuya, K., Harada, K., Odate, T., 1995. Primary production and community respiration in the East China Sea in winter and fall. In: Tsunogai, S., Iseki, K., Koike, I., Oba, T. (Eds.), Global Fluxes of Carbon and its Related Substances in the Coastal Sea–Ocean–Atmosphere System. M&J International, Yokohama, pp. 84–89.

Gardner, W.D., 1980. Sediment trap dynamics and calibration: A laboratory evaluation. J. Mar. Res. 38, 17–39.

Guptha, M.V.S., Curry, W.B., Ittekkot, V., Muralinath, A.S., 1997. Seasonal variation in the flux of planktic foraminifera: sediment trap results from the Bay of Bengal, northern Indian Ocean. J. Foraminif. Res. 27, 5–19.

Hama, T., Shin, K.H., Handa, N., 1997. Spatial variability in the primary productivity in the East China Sea and its adjacent waters. J. Oceanogr. 53, 41–51.

Honjo, S., 1978. Sedimentation of materials in the Sargasso Sea at a 5,367 m deep station. J. Mar. Res. 36, 469–492.

Honjo, S., Spencer, D.W., Farrington, J.W., 1982. Deep advective transport of lithogenic particles in Panama Basin. Science 216, 516–518.

Hoshika, A., Tanimoto, T., Mishima, Y., Iseki, K., Okamura, K., 1995. Seasonal variability in particle distributions and fluxes in the East China Sea. In: Tsunogai, S., Iseki, K., Koike, I., Oba, T. (Eds.), Global Fluxes of Carbon and its Related Substances in the Coastal Sea–Ocean–Atmosphere System. M&J International, Yokohama, pp. 171–176.

Imai, M., Ebara, S., Kawashima, K., Kubo, N., Sato, N., Moriyama, E., 1988. Seasonal variation of chlorophyll-*a* in the seas around Japan. Oceanogr. Mag. 38, 23–32.

Inoue, Y., 1989. Northwest Pacific foraminifera as paleoenvironmental indicators. Sci. Rept. Geosci. Univ. Tsukuba B (Geol. Sci.) 10, 57–162.

Ito, T., Kaneko, A., Furukawa, H., Gohda, N., Koteruyama, W., 1995. A structure of the Kuroshio and its related upwelling on the East China Sea shelf slope. J. Oceanogr. 51, 267–278.

Kaneko, A., Gohda, N., Koterayama, W., Nakamura, M., Mizuno, S., Furukawa, H., 1993. Towed ADCP fish with depth and roll controllable wings and its application to the Kuroshio observation. J. Oceanogr. 49, 383–395.

Oguri, K., Matsumoto, E., Saito, Y., Hama, T., Yamada, M., Narita, H., Iseki, K., 1997. Rate of sediment accumulation and carbon burial measured with 210Pb in the East China Sea. In: Tsunogai, S. (Ed.), Biogeochemical Processes in the North Pacific. Japan Marine Science Foundation, Tokyo, pp. 360–367.

Reynolds, L., Thunell, R.C., 1985. Seasonal succession of planktonic foraminifera in the subpolar North Pacific. J. Foraminif. Res. 15, 282–301.

Sugimoto, T., Kimura, S., Miyaji, K., 1988. Meander of the Kuroshio front and current variability in the East China Sea. J. Oceanogr. Soc. Jpn. 44, 125–135.

Takahashi, K., Bé, A.W.H., 1984. Planktic foraminifera: Factors controlling sinking speeds. Deep-Sea Res. 31, 1477–1500.

Takemoto, A., Oda, M., 1997. New planktic foraminiferal transfer functions for the Kuroshio–Oyashio Current Region off Japan. Paleontol. Res. 1, 291–310.

Tanaka, Y., 1997. Sedimentary processes from the shelf edge to the Okinawa Trough in the East China Sea based on the coccolith assemblage (in Japanese with English abstract). J. Sediment. Soc. Jpn. 44, 33–41.

Thunell, R.C., Honjo, S., 1981. Planktic foraminiferal flux to the deep ocean: Sediment trap results from the tropical Atlantic and the central Pacific. Mar. Geol. 40, 237–253.

Thunell, R.C., Reynolds, L.A., 1984. Sedimentation of planktic foraminifera: Seasonal changes in species flux in the Panama Basin. Micropaleontology 30, 243–260.

Thunell, R.C., Curry, W.B., Honjo, S., 1983. Seasonal variation in the flux of planktic foraminifera: time series sediment trap results from the Panama Basin. Earth Planet. Sci. Lett. 64, 44–55.

Walton, W.R., 1952. Techniques for recognition of living foraminifera. Contrib. Cushman Found. Foraminif. Res. 3, 56–60.

Watanabe, Y., Abe, K., Kusakabe, M., 1995. Characteristics of the nutrients distribution in the East China Sea. In: Tsunogai, S., Iseki, K., Koike, I., Oba, T. (Eds.), Global Fluxes of Carbon and its Related Substances in the Coastal Sea–Ocean–Atmosphere System. M&J International, Yokohama, pp. 54–60.

Xu, X., Oda, M., 1999. Surface-water evolution of the eastern East China Sea during the last 36,000 years. Mar. Geol. 156, 285–304.

Yamada, M., Aono, T., Narita, H., 1995. ^{210}Pb in settling particles on the East China Sea continental margin: The 1993–1994 MASFLEX. In: Tsunogai, S., Iseki, K., Koike, I., Oba, T. (Eds.), Global Fluxes of Carbon and its Related Substances in the Coastal Sea–Ocean–Atmosphere System. M&J International, Yokohama, pp. 226–231.

Yanagi, T., Shimizu, T., Lie, H.-J., 1998. Detailed structure of the Kuroshio frontal eddy along the shelf edge of the East China Sea. Cont. Shelf Res. 18, 1039–1056.