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Particulate fluxes of carbonate and organic carbon in the ocean. Is the marine biological activity working as a sink of the atmospheric carbon?

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ABSTRACT

The particulate fluxes of carbonate carbon and organic carbon observed in various oceans have been summarized in this paper and discussed with special reference to the fate of the atmospheric carbon dioxide. The organic carbon fluxes, which act as a sink of atmospheric carbon dioxide, are generally larger than the carbonate carbon fluxes working as a source, but are comparable in the deep subtropical oceans. The areal and vertical variations of the carbonate carbon fluxes are much smaller than those of the organic carbon fluxes, indicating that organisms producing carbonate particles exist rather evenly in the world ocean and that a substantial part of carbonate produced is transported to the ocean bottom. The particulate fluxes are much larger in the coastal and hemipelagic seas. Although the productivity of shallow seas holds a key role in the fate of anthropogenic carbon, the marine biota may not be a large sink when longer time scales are considered. The carbonate carbon fluxes in the productive northern Pacific are larger in the northeast Pacific than in the northwest Pacific, reflecting a difference in the ecosystems. This suggests that the eutrophication of marine environments may not necessarily act as a sink for the atmospheric carbon dioxide.

1. Introduction

The biological fixation of dissolved carbon dioxide in seawater (e.g., Koblentz-Mishke et al., 1970; Eppley, 1989) is even now 5–7 times larger than the amount of carbon dioxide evolved by the combustion of fossil fuels (e.g., NASA, 1988). Thus the marine biota could hold a key role in the fate of increasing carbon dioxide in the atmosphere even though the photosynthetic process and respiration balance out at present (Eppley and Peterson, 1979).

The production of organic carbon in the surface seawater is certainly a sink of the atmospheric carbon dioxide, because the marine organisms take up molecular carbon dioxide or carbonic acid from seawater to make soft tissue. Most of the synthesized organic carbon, however, is rather quickly decomposed in the water column or on the surface sediment (Ogura, 1972), while a part of organic carbon produced is buried in the coastal sediments (Walsh et al., 1985) or transported to the deep ocean (Biscaye et al., 1988).

On the other hand, the production of hard carbonate tests by organisms acts inversely as a source of atmospheric carbon dioxide (e.g., Broecker and Peng, 1982), unless an equilibrium process between clay minerals and seawater is effective. The process between clay minerals and seawater (e.g., Garrels and Mackenzie, 1971) is of a long time scale, because the residence times of major cations in seawater are longer than a few million years (Goldberg et al., 1971). Therefore, the increase in calcareous organisms by corals, shells of shellfishes and planktons such as foraminifera and coccolithophorids, induces the escape of carbon dioxide from seawater to the atmosphere. In contrast to organic carbon, a substantial part of biogenic carbonate in the ocean, especially in coastal seas supersaturated with respect to calcium carbonate (calcite or aragonite), is buried in the bottom sediments and its dissolution occurs only in deep water.

We should give attention not only to absolute amounts of carbonate and organic carbon produced and decayed, but also to their relative ratios, because the marine biological activity has no net effect on the atmospheric CO_2 if the ratio of preserved carbonate carbon to organic carbon is unity. The fates of particulate organic carbon and carbonate carbon can be estimated partly from dissolved components such as oxygen, total carbonate and alkalinity in the subsurface water altered by the decay of these particles. The water, however, moves and mixes. Complicated models to predict the dynamics of water are hard to solve for the dissolved components (e.g., U.S. GOFS Planning Report No. 4, 1987), and simplified models such as box models and one-dimensional diffusion and advection models (e.g., Riley, 1951; Craig, 1969, 1971; Tsunogai, 1972) give only crude values. Moreover, the model calculation for the dissolved components in water does not give information on the fraction not dissolved.

Recent sediment trap experiments (Honjo, 1980; Wefer et al., 1982; Karl and Knauer, 1984; Dymond and Lyle, 1985; Emerson et al., 1985; Deuser, 1986; Tsunogai and Noriki, 1987; Biscaye et al., 1988; Dymond and Collier, 1988; Karl et al., 1988; Walsh et al., 1988; Wefer et al., 1988) can provide valuable information on the production and fate of carbonate and organic carbon. Although the experiments are only of a reconnaissance scale now, it may be worthwhile to synthesize individually published data, including unpublished data obtained by our group, into a global picture.

2. Data sources

More than half the data used in this study (Table 1 and Fig. 1) were obtained by our Hokkaido University group. Description of the moorings and the sample treatment have been already given (Tsunogai et al., 1982, 1986; Noriki and Tsunogai, 1986; Kusakabe et al., 1988; Taguchi et al., 1989; Masuzawa et al., 1989). Two types of sediment trap were used. One is the NH type consisting of 6 cylinders of 25 cm in diameter and 60 cm high. The NH-type traps were used for the collection of a single sample for the deployment period usually less than 1 month. The other is the double-cone ND traps of 40 cm in diameter equipped with 4–9 cups for the time series trapping. We can compare replicate

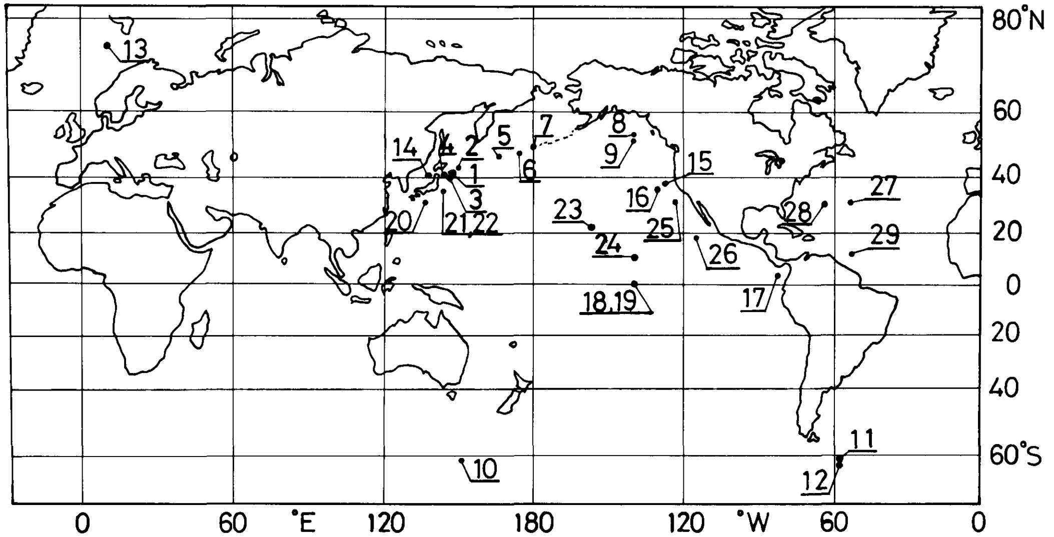

Fig. 1. Map showing stations for the sediment trap experiments carried out or cited in this study. The numerals given in the figure correspond to the station numbers in Table 1.

Table 1. *Stations for the sediment trap experiments carried out or cited in this study*

Station No.&Code	Location	Month/year	Days set**	Total depth (m)	Ref.
High-latitudes zone					
Western North Pacific					
1 WP-1	40°31'N, 146°28'E	8/83– 9/83	18	5160	this work*
2 WP-2	43°00'N, 150°14'E	4/85– 5/85	13	5020	this work*
3 WP-3	40°00'N, 145°26'E	9/84– 4/85	220	5270	this work
4 EM	40°55'N, 141°59'E	9/88– 5/89	260	5370	this work
Central North Pacific					
5 NP-B	46°49'N, 162°07'E	8/85– 6/86	296	5670	this work
6 NP-T	47°51'N, 176°21'E	7/78– 8/78	31	5300	this work*
7 NP-3	49°03'N, 179°58'E	6/89– 8/89	45	5140	this work
Eastern North Pacific					
8 GA-2	53°03'N, 145°00'W	6/86– 7/86	16	4110	this work
9 PAPA	50°00'N, 145°00'W	3/83–10/83	192	4200	1, 2
Antarctic Ocean					
10 AO	61°33'S, 150°27'E	12/83– 1/84	24	3580	this work*
11 DP-W	60°55'S, 57°06'W	12/80– 1/81	52	3625	3
12 BS-W	62°15'S, 57°31'W	12/83–11/84	360	1952	4
Northern Norwegian Sea					
13 NNS	75°51'N, 11°28'E	8/84– 7/85	360	2123	5
Japan Sea					
14 JS	40°50'N, 138°42'E	9/84	13	3350	this work*
Transitional and equatorial zone					
Eastern North Pacific					
15 EP-1	37°00'N, 127°34'W	12/82	7	4750	this work*
16 EP-M	35°40'N, 123°50'W	8/81– 9/81	-	-	6
Panama Basin					
17 PB-H	5°21'N, 81°53'W	8/79–12/79	112	3856	7
Equatorial Pacific					
18 C1-D	1°N 139°W	12/82– 2/84	14 m	4470	8
19 C2-D	1°N 139°W	2/84– 5/85	14 m	4470	8
Low-latitudes zone					
Western North Pacific					
20 SB-1	31°32'N, 137°08'E	1/87– 3/87	44	4300	this work
21 JT-1	34°10'N, 141°59'E	8/86– 5/87	247	9200	this work
22 JT-3	34°10'N, 141°59'E	6/87–11/88	17 m	9200	9
Central North Pacific					
23 P-H	15°21'N, 151°28'W	9/78–11/78	61	5792	10
24 S-DY	11°N, 140°W	12/82– 2/84	14 m	4260	8
Eastern North Pacific					
25 EP-2	31°42'N, 124°25'W	12/82– 1/83	40	4200	this work*
26 EP-3	17°29'N, 116°01'W	12/82– 1/83	24	3870	this work*
North Atlantic					
27 S-H	31°32'N, 55°55'W	7/77–10/77	110	5581	10
28 S-DE	32°05'N, 64°15'W	4/78– 5/84	6 y	4200	11
29 E-H	13°30'N, 54°00'W	11/77– 2/78	98	5288	10
Hemipelagic zone					
30 Sh-1	41°16'N, 142°16'E	6/78	4	1265	this work*
31 Sh-2	41°15'N, 142°24'E	5/80	3	1340	this work*
32 Sa-1	35°02'N, 139°18'E	6/79– 7/79	30	1440	this work*
33 Sa-2	35°00'N, 139°15'E	6/81– 7/81	32	1360	this work*

References: (1) Reynolds and Thunell (1985); (2) Takahashi (1986); (3) Wefer et al. (1982); (4) Wefer et al. (1988); (5) Honjo et al. (1988); (6) Martin and Knauer (1983); (7) Honjo (1980); (8) Dymond and Collier (1988); (9) Honjo (1989); (10) Honjo et al. (1982); (11) Deuser (1986).

* Its organic carbon flux has been given in Tsunogai and Noriki (1987).

** m: months; y: years.

flux measurements. The organic carbon contents except some new results have previously been reported together with the determination method (Tsunogai and Noriki, 1987). The carbonate carbon contents have been calculated from the acid-soluble Ca contents, determined by an atomic absorption method. Various constituents other than organic carbon and acid soluble Ca in the same sediment trap samples have been determined simultaneously.

In this study, we have also used the data obtained by other authors, especially in the Atlantic and the East Pacific (Table 1). When we used the NH-type traps, the 95% confidence limits of the total mass fluxes ranged from 20 to 40% around the mean values, and the analytical errors for each determination were 1–10%. We made every effort to minimize errors due to the trapping efficiency by considering the geometry of traps including baffles and by using preservatives (formaldehyde and sodium azide). The seasonal variation (e.g., Wefer et al., 1988) and even the interannual variation (e.g., Deuser, 1986) in particulate fluxes, however, is usually larger than the uncertainties caused by the experimental errors for each observation. The data given in this study are therefore not the definitive mean values of occupied observation stations, but each value rather represents only the situation when the observation was made. The data obtained by the time series observations were averaged for whole periods. It may be possible to extract somewhat more definitive features from the many data, however, even though every single value is not highly meaningful.

3. Results and discussion

All the cabonate and organic carbon fluxes obtained and their ratios are plotted in Figs. 2–4.

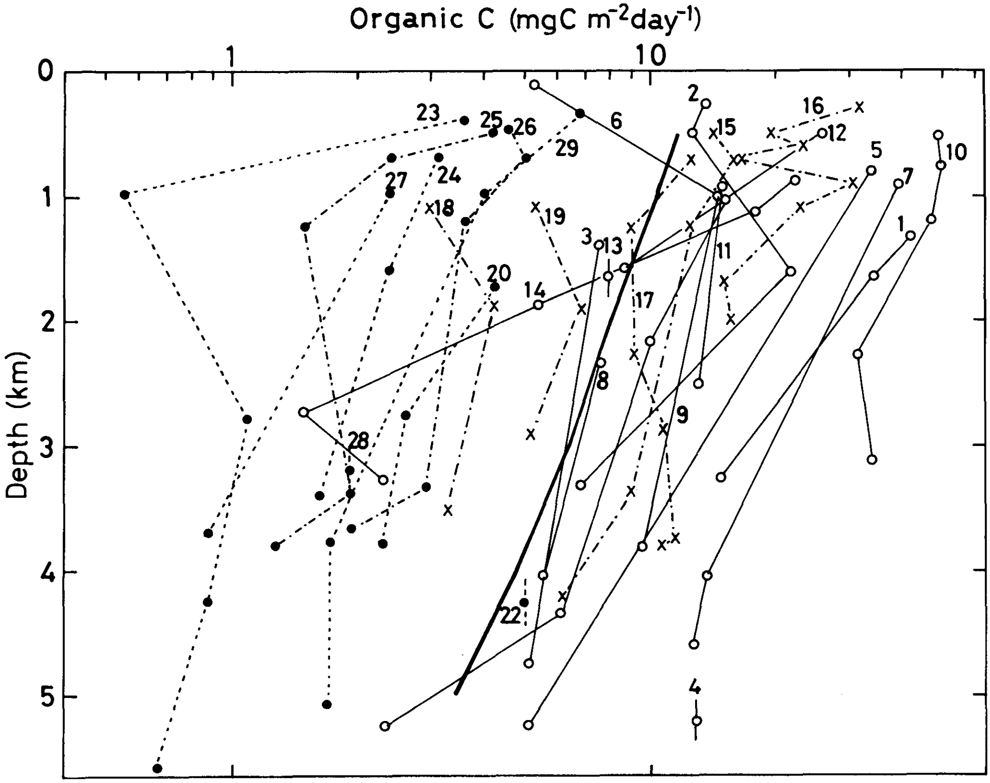

Fig. 2. Observed organic carbon fluxes. Open circles are from the high-latitudes (>40°), crosses are from the transitional and equatorial zone, and solid circles are from the low-latitudes zone (<35°). A thick line is composed of median values. The numerals attached refer to the station numbers given in Table 1 and Fig. 1.

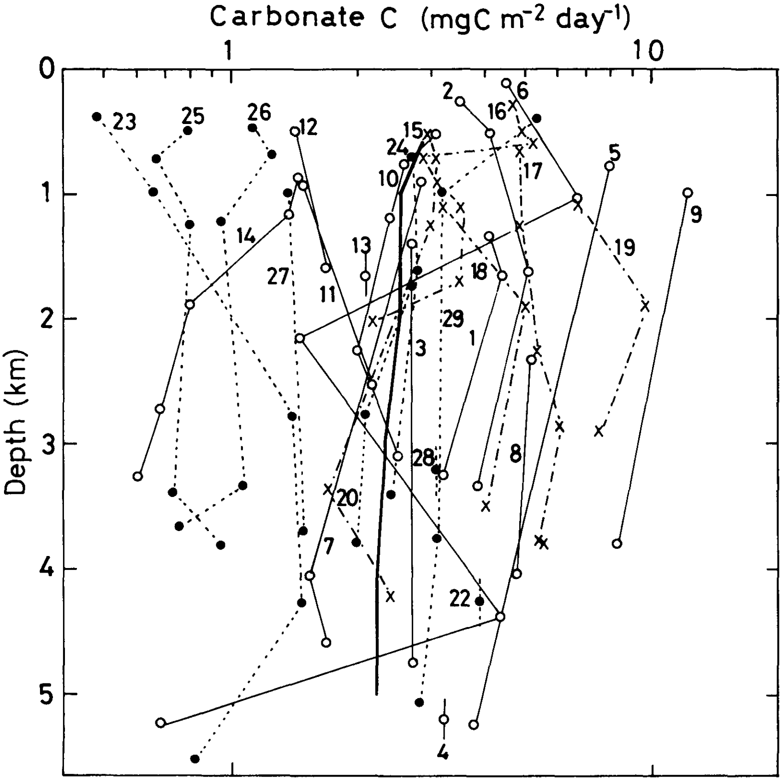

Fig. 3. Observed carbonate fluxes. Notation is the same as that in Fig. 2.

The fluxes at 0.5, 1, 2, 3, 4 and 5 km depths estimated by interpolation are listed in Table 2. The results obtained in the hemipelagic zone are given in Table 3.

3.1. Organic carbon fluxes

The calculation obtained for the organic carbon fluxes is the same as that given in our previous paper (Tsunogai and Noriki, 1987), although some new data have been added. The organic carbon flux is one order of magnitude larger in the high-latitudes, namely north of the polar front (ca. 40° N) in the North Pacific, than in warm subtropical oceans (Table 2). Table 3 shows that the flux in the coastal and hemipelagic seas is sometimes two orders of magnitude larger than that in the warm ocean, except for the equatorial region. These results suggest that the marine environment can be fairly distinctly divided into 3 parts for organic matter production: the warm oceans covering roughly 60% of the total sea area (where the organic carbon flux is 2–5 mgC m^{-2} day^{-1} at 1 km depth); the cold oceans covering 30% (10–40 mgC m^{-2} day^{-1} at 1 km depth); the coastal and hemipelagic seas covering 10% (probably more than 100 mgC m^{-2} day^{-1} to the bottom or at 1 km depth as deduced from Table 3, and Noriki et al. (1985)).

For the vertical variation, the median values of the observed organic carbon fluxes decrease by 24% at intervals of 1 km depth (Fig. 2), which is the same as in previous results (Tsunogai and Noriki, 1987), but this coefficient may be larger in the shallower subsurface water of warm oceans as obtained by Suess (1980) and Martin et al. (1987), because the observed particulate flux is much smaller than the primary production in the warm water. We use median values calculated in the same way as in Tsunogai and Noriki (1987). The median values are usually about 1/2 the arithmetic mean values, which are apt to be affected by larger values in widely scattered data.

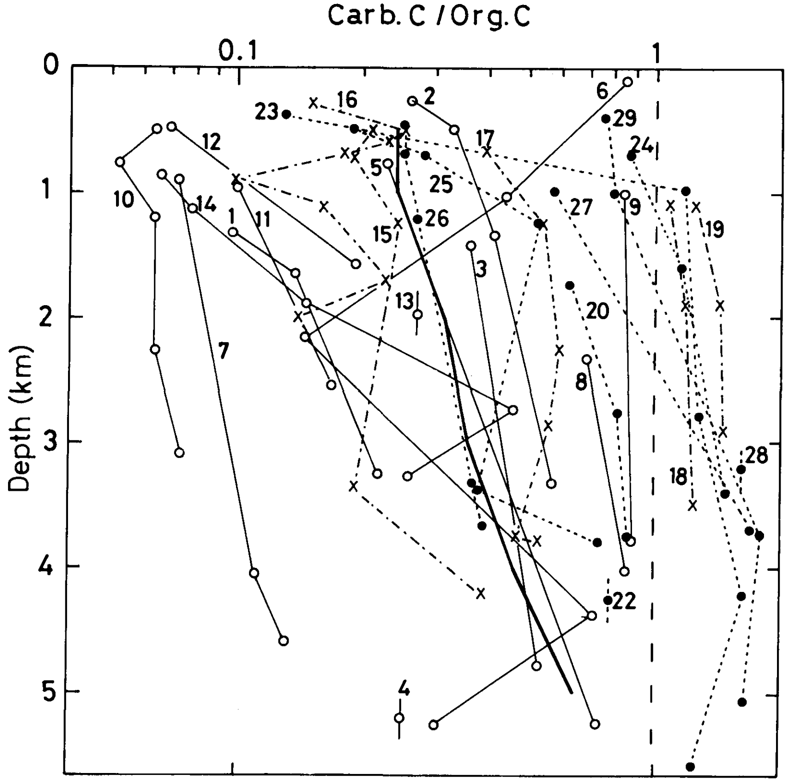

Fig. 4. Ratios of carbonate carbon to organic carbon. Notation is the same as that in Fig. 2.

Decomposition rates based on the median values of organic matter in the subsurface waters are 2.4, 2.4, 1.6, 1.6 and 1.4 μgC m^{-3} day^{-1} or 1.3, 1.3, 0.9, 0.9 and 0.8 ml O_2 m^{-3} yr^{-1}, respectively, for the water columns of 0.5–1, 1–2, 2–3, 3–4 and 4–5 km depth. The conversion factor from the organic carbon oxidation to the dissolved oxygen consumption used is of that obtained by Tsunogai (1972). The integrated amounts of decomposed organic carbon are 8.2 and 3.4 mgC m^{-2} day^{-1} or 3.0 and 1.2 gC m^{-2} yr^{-1}, respectively, for the water columns of 0.5–5 km and below 5 km, including the activity on the bottom. The oxygen consumption rates calculated from the particulate flux for the water column of 0.5–2 km depth are far less than those calculated from the dissolved oxygen distribution, ignoring the lateral mixing of deep water with that in the continental margin area (Riley, 1951; Craig, 1971; Tsunogai, 1972; Jenkins, 1982). The cause of the difference is still controversial. It is possible that the dissolved oxygen is consumed by the oxidation of dissolved organic matter in the pelagic deep water (Toggweiler, 1989) or by the oxidation of particulate organic carbon produced in the coastal and hemipelagic seas (Walsh et al., 1981; Tsunogai and Noriki, 1987).

3.2. *Carbonate carbon flux*

Both the areal and vertical variations of the carbonate carbon fluxes are smaller than those of the organic carbon fluxes, although the carbonate fluxes decrease slightly with depth (Fig. 3). The areal variation is a factor of 2.2 (1σ at 2 km depth on the logarithmic scale), which is 50% smaller than that of organic carbon fluxes (a factor of 3.1). The median values of carbonate carbon fluxes are 2.6 and 1.4 mgC m^{-2} day^{-1} at 2 km depth for the high- and low-latitudes, respectively, whereas those of organic carbon fluxes are 14 and 2.2 mgC m^{-2} day^{-1}. The vertical decrease is only 5% per km in depth, showing little dissolution during sinking through the water column even in the North Pacific where the water is undersaturated with respect to $CaCO_3$.

The median values also show that the dissolution rate of $CaCO_3$ in the water column from 0.5 to 5 km depth is 0.7 $mgC\ m^{-2}\ day^{-1}$ or 57 $\mu gC\ m^{-3}\ yr^{-1}$ or 2.1 $gCaCO_3\ m^{-2}\ yr^{-1}$, whereas the carbonate carbon transported below 5 km depth is 2.2 $mgC\ m^{-2}\ day^{-1}$ or 6.7 $gCaCO_3\ m^{-2}\ yr^{-1}$. The dissolution rate of $CaCO_3$ in the water column is much smaller than that calculated from the alkalinity change in the subsurface water (Craig, 1969) or from the Ca distribution (Tsunogai et al., 1973), which is 480 $\mu gC\ m^{-3}\ yr^{-1}$. This discrepancy indicates that $CaCO_3$ is dissolved at the bottom of biologically productive seas, and that the water increased in carbonate is laterally well mixed. This is the same for organic carbon as stated above, but carbonate shows the pattern more strongly.

Even if a large seasonal variation changes somewhat the mean values of carbonate flux in the productive northern North Pacific, the carbonate carbon flux in the northeastern Pacific (9 $mgC\ m^{-2}\ day^{-1}$ at 2 km depth) is larger than in the northwestern Pacific (4 $mgC\ m^{-2}\ day^{-1}$). The dif-

Table 2. *Particulate fluxes of organic carbon (A) and carbonate carbon (B) and the ratios of carbonate to organic carbon fluxes (C) at the 0.5, 1, 2, 3, 4 and 5 km levels estimated from their vertical profiles by interpolation*

(A) Organic carbon fluxes ($mgC\ m^{-2}\ day^{-1}$)

Code	0.5 km	1 km	2 km	3 km	4 km	5 km
High-latitudes zone						
Western North Pacific						
1 WP-1	-	49	28	17	10	-
2 WP-2	13	17	18	9.6	-	-
3 WP-3	-	7.8	7.1	6.3	5.6	-
4 EM	-	-	-	-	-	12.8
Central North Pacific						
5 NP-B	-	32	26	20	13	6.7
6 NP-T	10	15	10	8.6	5.6	3.3
7 NP-3	-	39	30	22	14	-
Eastern North Pacific						
8 GA-2	-	-	8.0	6.8	5.5	-
9 PAPA	-	15	13	11	9.2	-
Antarctic Ocean						
10 AO	49	43	33	34	-	-
11 DP-W	-	15	14	-	-	-
12 BS-W	26	18	-	-	-	-
Northern Norwegian Sea						
13 NNS	-	-	7.9	-	-	-
Japan Sea						
14 JS	-	20	4.6	1.9	-	-
Median (H)*	-	17	14	12	8.8	-
	(-)	(1.23)	(≡1)	(0.85)	(0.63)	(-)

(A) Organic carbon fluxes ($mgC\ m^{-2}\ day^{-1}$)

Code	0.5 km	1 km	2 km	3 km	4 km	5 km
Transitional and equatorial zone						
Eastern North Pacific						
15 EP-1	14	14	11	9.3	6.8	-
16 EP-M	20	26	15	-	-	-
Panama basin						
17 PB-H	13	11	9.1	11	-	-
Equatorial Pacific						
18 C1-D	-	2.9	4.2	3.6	-	-
19 C2-D	-	5.3	6.6	5.1	-	-
Low-latitudes zone						
Western North Pacific						
20 SB-1	-	5.5	3.9	2.5	-	-
21 JT-1	-	-	-	-	-	4.6**
22 JT-3	-	-	-	-	5	-
Central North Pacific						
23 P-H	3.5	2.4	1.5	1.0	0.91	0.76
24 S-DY	-	2.9	2.2	1.8	-	-
Eastern North Pacific						
25 EP-2	4.2	2.2	1.8	1.4	1.2	-
26 EP-3	4.7	4.2	3.2	3.0	1.7	-
North Atlantic						
27 S-H	-	2.4	1.6	1.1	0.78	-
28 S-DE	-	-	-	1.9	-	-
29 E-H	6.3	3.9	2.8	2.1	1.6	1.7
Median (L)*	-	2.9	2.2	1.8	1.4	-
	(-)	(1.32)	(≡1)	(0.82)	(0.64)	(-)
Median (total)*	11.6	10.4	8.0	6.4	4.8	3.4
	(1.45)	(1.30)	(≡1)	(0.80)	(0.60)	(0.42)

* The medians are obtained for the high-latitudes (H), low-latitudes (L) and total zones based on the ratios of the fluxes to that at 2 km depth at each station.

** The observed values at 8.8 km depth.

Table continued

Table 2 (*continued*)

(B) Carbonate carbon fluxes (mgC m^{-2} day^{-1})

Code	0.5 km	1 km	2 km	3 km	4 km	5 km
High-latitudes zone						
Western North Pacific						
1 WP-1	-	4.1	4.2	3.4	2.7	-
2 WP-2	4.1	4.5	4.8	4.1	-	-
3 WP-3	-	2.7	2.7	2.7	2.7	-
4 EM	-	-	-	-	-	3.2
Central North Pacific						
5 NP-B	-	7.7	6.8	5.9	5.0	4.0
6 NP-T	5.4	6.6	2.2	2.6	3.9	1.7
7 NP-3	-	2.8	2.4	2.0	1.5	-
Eastern North Pacific						
8 GA-2	-	-	5.2	5.0	4.8	-
9 PAPA	-	12	11	9.5	8.1	-
Antarctic Ocean						
10 AO	3.1	2.5	2.1	2.4	-	-
11 DP-W	-	1.5	2.0	-	-	-
12 BS-W	1.4	1.6	-	-	-	-
Northern Norwegian Sea						
13 NNS	-	-	2.1	-	-	-
Japan Sea						
14 JS	-	1.4	0.77	0.64		
Median (H)*	-	2.8	2.6	2.3	1.9	-
	(-)	(1.09)	(≡1)	(0.87)	(0.74)	(-)
Transitional and equatorial zone						
Eastern North Pacific						
15 EP-1	3.0	3.0	2.5	1.9	2.2	-
16 EP-M	4.9	3.4	2.2	-	-	-
Panama Basin						
17 PB-H	4.9	4.9	5.3	6.6	-	-
Equatorial Pacific						
18 C1-D	-	3.1	4.9	4.3	-	-
19 C2-D	-	6.7	9.5	7.4	-	-
Low-latitudes zone						
Western North Pacific						
20 SB-1	-	3.1	2.5	2.1	-	-
21 JT-1	-	-	-	-	-	0.88**
22 JT-3	-	-	-	-	3.9	-
Central North Pacific						
23 P-H	0.51	0.66	1.1	1.4	1.4	1.1
24 S-DY	-	2.7	2.7	2.5	-	-
Eastern North Pacific						
25 EP-2	0.79	0.74	0.78	0.74	0.94	-
26 EP-3	1.15	1.08	1.00	1.05	0.72	-
North Atlantic						
27 S-H	-	1.4	1.4	1.5	1.2	-
28 S-DE	-	-	-	3.1	-	-
29 E-H	4.8	3.2	3.2	3.1	3.0	3.1
Median (L)*	-	1.4	1.4	1.5	1.3	-
	(-)	(1.00)	(≡1)	(1.07)	(0.93)	
Median (total)*	2.9	2.5	2.5	2.3	2.2	2.2
	(1.17)	(1.00)	(≡1)	(0.92)	(0.88)	(0.87)

(C) Ratios of carbonate to organic carbon fluxes

Code	0.5 km	1 km	2 km	3 km	4 km	5 km
High-latitude zone						
Western North Pacific						
1 WP-1	-	0.08	0.15	0.20	0.27	-
2 WP-2	0.32	0.26	0.27	0.43	-	-
3 WP-3	-	0.35	0.38	0.43	0.48	-
4 EM	-	-	-	-	-	0.25
Central North Pacific						
5 NP-B	-	0.24	0.26	0.30	0.38	0.60
6 NP-T	0.54	0.44	0.22	0.30	0.62	0.52
7 NP-3	-	0.07	0.08	0.09	0.11	-
Eastern North Pacific						
8 GA-2	-	-	0.65	0.74	0.87	-
9 PAPA	-	0.80	0.85	0.86	0.88	-
Antarctic Ocean						
10 AO	0.06	0.06	0.06	0.07	-	-
11 DP-W	-	0.10	0.14	-	-	-
12 BS-W	0.05	0.09	-	-	-	-
Northern Norwegian Sea						
13 NNS	-	-	0.27	-	-	-
Japan Sea						
14 JS	-	0.07	0.17	0.34	-	-
Median (H)*	-	0.17	0.19	0.19	0.22	-
	(-)	(0.89)	(≡1)	(1.02)	(1.17)	(-)
Transitional and equatorial zone						
Eastern North Pacific						
15 EP-1	0.21	0.21	0.23	0.20	0.32	-
16 EP-M	0.24	0.13	0.15	-	-	-
Panama basin						
17 PB-H	0.38	0.45	0.58	0.60	-	-
Equatorial Pacific						
18 C1-D	-	1.07	1.17	1.19	-	-
19 C2-D	-	1.26	1.44	1.45	-	-
Low-latitudes zone						
Western North Pacific						
20 SB-1	-	0.56	0.64	0.84	-	-
21 JT-1	-	-	-	-	-	0.19**
22 JT-3	-	-	-	-	0.78	-
Central North Pacific						
23 P-H	0.15	0.28	0.73	1.40	1.54	1.45
24 S-DY	-	0.93	1.23	1.39	-	-
Eastern North Pacific						
25 EP-2	0.19	0.34	0.43	0.53	0.78	-
26 EP-3	0.24	0.26	0.31	0.35	0.42	-
North Atlantic						
27 S-H	-	0.58	0.88	1.36	1.54	-
28 S-DE	-	-	-	1.63	-	-
29 E-H	0.76	0.82	1.14	1.48	1.88	1.82
Median (L)*	-	0.48	0.64	0.83	0.93	-
	(-)	(0.75)	(≡1)	(1.30)	(1.45)	(-)
Median (total)*	0.25	0.24	0.31	0.36	0.45	0.65
	(0.81)	(0.77)	(≡1)	(1.15)	(1.47)	(2.07)

Table 3. *Organic and carbonate carbon fluxes observed in the hemipelagic zone*

	Depth (m)	Total flux (mg m $^{-2}$ day $^{-1}$)	Organic C flux (mgC m $^{-2}$ day $^{-1}$)	Carbonate C flux (mgC m $^{-2}$ day $^{-1}$)
Sh-1	320	117	17.6	-
	1160	277	18.4	-
Sh-2	150	3020	258	3.6
	1060	5530	295	10.6
	1285	4920	281	6.2
Sa-1	240	690	93	-
	1190	2870	208	-
Sa-2	310	750	84.5	9.3
	620	700	47.2	7.6
	1150	890	50.4	9.4

ference is probably due to the difference in the ecosystems. According to Parsons (1988), the eastern North Pacific is classified as the upwelled biome and the western North Pacific as the spring bloom biome with high silica. The former is more productive for calcareous plankton than the spring bloom biome with high silica, because the latter produces diatoms abundantly, due to the higher Si/P ratio of water just below the euphotic layer in the western North Pacific (Tsunogai, 1987). Eutrophication caused by anthropogenic nitrate and phosphate may produce more calcareous matter, because it does not increase silica in water, i.e., diatoms (Tsunogai and Watanabe, 1983).

3.3. Ratios of carbonate carbon fluxes to organic carbon fluxes

The highest ratio of carbonate carbon to organic carbon fluxes has been found in the subtropical Atlantic to be 1.1 at 2 km depth or 1.9 at 4 km depth, whereas the lowest has been found to be 0.06 at 2 km depth or 0.07 at 4 km depth in the Antarctic Ocean. The highest ratio is probably due to the propagation of coccolithophorids in the warm oligotrophic Atlantic water, where biological activity works as a source for atmospheric carbon dioxide rather than as a sink, if we consider the net biological production in the surface water.

Noriki and Tsunogai (1986) have stated that the areal variation of carbonate carbon flux is small and that the organic carbon flux increases fairly proportionally with the biogenic silica flux. According to them, the ratio of carbonate carbon flux to organic carbon flux is inversely correlated with the organic carbon flux, and the ratio is smaller in the more productive oceans. The lowest ratio found in the Antarctic Ocean qualitatively confirms their statement.

The ratios of carbonate to organic carbon fluxes increase with depth for the median values which are 1/4 at 1 km depth and about 1/2 at 4 km depth. Although the role of coastal and hemipelagic seas in the carbon cycle may be large as discussed by Walsh et al. (1981), the mean pelagic ocean certainly acts as a sink for the atmospheric carbon dioxide if we consider a time scale less than the ventilation time of the deep water; however, the function of organic carbon production as a sink is largely compensated by the production of carbonate particles, and decreases with time.

4. Conclusion

The marine biota cannot be simply regarded as a sink of the atmospheric carbon dioxide of anthropogenic origin, although the organic carbon flux working as a sink of the atmospheric carbon is larger than the carbonate carbon flux as a source in the pelagic ocean, except in the subtropical Atlantic. The source or sink strength of the marine biota for the atmospheric carbon depends highly on the time scale considered, because the proportion of preserved material at the bottom and in the deep water is larger for carbonate. The effects of production and decomposition or dissolution of organic and carbonate carbon in the coastal and hemipelagic seas, and of the lateral mixing of water on the carbon cycle, are extremely large. Our data are still insufficient to discuss this matter quantitatively. The effects should be studied on a world-wide scale. In the pelagic oceans, it is also necessary to study more closely and extensively the lateral transport of these particles and water, including the areal and temporal variations of fluxes of carbonate and organic carbon.

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