Seasonal and vertical variations of sinking particle fluxes in the West Caroline Basin

Hodaka KAWAHATA [a,b], **Masumi YAMAMURO** [a], **Hidekazu OHTA** [c]

[a] Marine Geology Department of Geological Survey of Japan, 1-1-3 Higashi Tsukuba, Ibaraki, 305, Japan
(E-mail: kawahata@gsj.go.jp)
[b] Graduate School of Science, Tohoku University, Sendai, 980-77, Japan
[c] Kansai Environmental Engineering Center, Osaka, Japan

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Abstract – A sediment trap experiment was carried out in the West Caroline Basin, located in the equatorial western Pacific between influences of the Asian monsoon and the open ocean. Annual mass flux at the shallow trap at Site 1 was 57.10 g $m^{-2}yr^{-1}$. Generally, the higher flux of organic matter was associated with higher activities of biogenic opal-producing and carbonate-producing plankton communities. In addition, as the organic matter content increases, the organic carbon/carbonate carbon ratio shows a tendency to increase. Carbonate-producing plankton was predominant during periods 1 and 3 (May to July and November to the beginning of December), which could be due to limited silica supply to the euphotic zone. On the other hand, surface sea water was more nutrient-rich during periods 2 and 4 (August to October and the end of December to April) at Site 1. These high total mass fluxes could be stimulated by wind.
The amount of biogenic components collected in the sediment traps and the accumulation in surface sediments at Site 1 could be compared with primary productivity values. Carbonate and biogenic opal fluxes were 99 % and 90 % less, respectively, in the surface sediments compared to those in the shallow sediment trap. This could be due to the reaction of sinking particles with undersaturated deep sea water just above the sea floor, rather than with the water column during sinking. About 20 % of the organic matter was decomposed between the shallow and deep sediment traps and more than 98 % between the deep sediment trap and final burial in the surface sediments. The relative amount of organic carbon preserved in surface sediments was about 0.10 % of annual primary productivity. © Elsevier, Paris

seasonality /vertical variations / sinking particle fluxes / Western Pacific / carbon cycle

Résumé – Variations saisonnières et verticales des flux de particules dans le bassin des Carolines. Des pièges à sédiments ont été déployés dans le bassin des Carolines Occidentales (ouest du Pacifique équatorial), entre la zone d'influence de la mousson d'Asie et l'océan ouvert. À la station 1, le flux annuel au piège le moins profond est 57,10 g m^{-2} an^{-1}. Les flux élevés de matière organique sont généralement associés au développement des communautés planctoniques à test siliceux et carbonaté. De plus, le rapport carbone organique/carbone minéral tend à augmenter avec la teneur en matière organique. Le plancton carbonaté prédomine pendant les périodes 1 et 3 (de mai à juillet et de novembre au début décembre), probablement en raison de l'apport limité en silice dans la couche euphotique. L'eau superficielle est enrichie en éléments nutritifs pendant les périodes 2 et 4 (d'août à octobre et de la fin décembre à avril) à la station 1. Ces flux élevés pourraient être favorisés par l'action du vent sur la surface océanique. La quantité de composés biogéniques collectés dans les pièges à sédiments et leur accumulation dans les sédiments superficiels du site 1 peuvent être comparées aux valeurs de productivité primaire. Les flux de carbonate et d'opale biogènes dans les sédiments de surface sont inférieurs, de 99 % et 90 % respectivement, aux flux dans le piège à sédiment le moins profond ; probablement par réaction des particules avec l'eau sous-saturée, à proximité du fond, plutôt que durant la chute des particules dans la colonne d'eau. Environ 20 % de la matière organique est décomposée entre les deux niveaux de pièges à sédiments, et plus de 98 % avant l'incorporation au sédiment. Le carbone organique préservé dans les sédiments superficiels représente environ 0,10 % de la productivité primaire annuelle. © Elsevier, Paris.

variation saisonnière / variation verticale / flux de particules / Pacifique occidental / cycle du carbone

1. INTRODUCTION

Sediment trap experiments conducted in various ocean basins show that particle fluxes to the deep sea are related to surface primary productivity. However, our knowledge about primary productivity and export production in the different geochemical provinces is rather limited. Up to now, extensive studies on sinking particles have been carried out in the Panama Basin of the eastern Pacific [12, 14], the central Pacific [6, 13] and the eastern Atlantic [30] in order to understand the carbon cycle and its seasonal variation in high production regimes of the equatorial region. However, little is know about the vertical transport of carbon by sinking particles in the western equatorial Pacific, where the surface waters are warm and nutrients come from terrestrial runoff. The West Caroline Basin in this area provides a good opportunity to investigate sinking particles in relation to the carbon cycle. This area is mainly influenced by nutrient supply from coastal regions in the Philippine and Indonesian Islands, and is affected by the South-East Asian monsoon climate.

The transfer of carbon from the surface to the deep sea and/or sea floor is another important key to understanding the carbon cycle. The degradation of organic matter in the intermediate and deep waters and near the sea floor is associated with dissolved oxygen consumption and regeneration of nutrients and total dissolved CO_2. Therefore, the change of downward flux of organic carbon and associated components and the shift in the Corganic/ Ccarbonate ratio through the water column and at the sediment-water interface need to be given consideration.

In order to understand the vertical flux of biological components and the relation between the formation of sinking particles and the meteorological factor, we collected sinking particles and surface sediments just below the trap mooring in the West Caroline Basin, which has warm surface waters and is affected by coastal currents.

2. STUDY AREA

The West Caroline Basin is located north of New Guinea (*figure 1*). The basin is surrounded by banks or islands in Melanesia, including the Palau Islands, to the west and north, and by the Eauripik rise to the east. The basin has a depth of 4000 m to 5000 m and hemipelagic sediments with a variety of carbonate contents are dominant in this area.

Three major currents are important in the West Caroline Basin (*figure 1*): the North Equatorial Current and its branch and the Equatorial Counter Current. The North Equatorial Current is a west-bound flow and is observed between 25° N and 5° N near 170–180° E in February, while in August it descends no lower than 10° N. On reaching the western end of the Pacific, the North Equatorial Current comes up against the continental barrier of the Philippines, where it divides into two branches. One branch turns to the south and feeds the east-bound Equatorial Counter Current [29].

3. METHODS

One mooring consisting of two SMD21-6000 (Nichiyu-giken-kogyou Ltd., Tokyo) time-series sediment traps with a collection area of 0.5 m^2 and 21-cup collectors on each was deployed at 2° 59.8' N, 135° 01.5' E (Site 1) in the West Caroline Basin (*figure 1*). The water depth at Site 1 was 4414 m. The shallow and deep traps were deployed at depths of 1592 m and 3902 m (500 m above the sea floor) at Site 1, respectively. The opening and closing of both the traps were synchronized with an error of less than two minutes and these periods are presented in *table I*.

Before deployment, sample bottles were filled with filtered sea water (0.45 μm filter) with the addition of analytical grade formalin to make a 3 % solution and buffered with sodium borate in order to retard bacterial activity in the trap material. Recovered samples were immediately refrigerated on board at approximately 2 to 4 °C. Particle samples in 250 mL polyethylene sample bottles were transported to the Geological Survey of Japan under refrigeration at 2 °C. Each trap sample was split into aliquots with a high precision splitter (McLaneWSD-10) after picking out all recognisable zooplankton "swimmers" by hand.

We used a desalted, homogenized 1/2 split from each sample for the bulk analysis. Organic carbon was determined with a Yanako MT-5 CHN analyser after removing carbonate by acidification within ceramic sample boats using HCl vapour. Samples were weighed out into precombusted ceramic boats and 100 μL ultra-pure water was pipetted into each sample boat [31]. The samples were reacted with HCl vapour to remove carbonate completely at room temperature for 24 h in a glass desiccator which contained 500 mL of 12N HCl. Then the samples were dried up to drive off HCl and water at 50 °C for at least 3 h, before determining carbon with the CHN analyser. No filtration step was involved. Total carbon and nitrogen measurements were also made on dried and

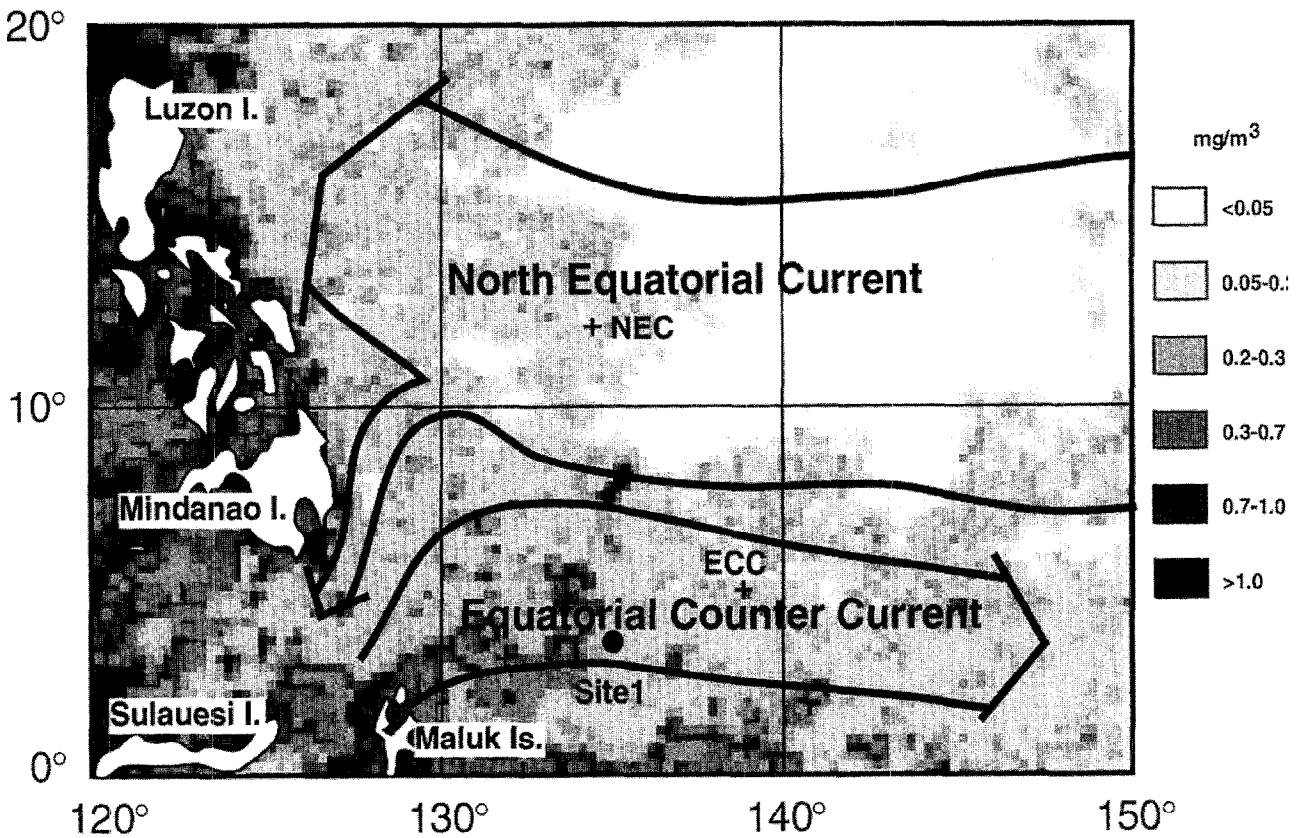

Figure 1. Locations of the mooring site and ocean surface current during spring of 1991 in the West Caroline Basin. Water depth at Site 1 was 4414 m and sediment traps were deployed at 1592 and 3902 m (500 m above the sea floor), respectively. Global phytoplankton pigment concentrations (mg m^{-3}) were revealed by three-month composites for October–December, 1979. The observations made from the Coastal Zone Color Scanner (CZCS), a radiometer that operated on NASA' Nimbus-7 satellite. NEC and ECC sites are located at 12° 01.00' N, 134° 17.16' E and 5° 00.60' N, 138° 49.81' E, respectively (Kempe and Knaack, 1996).

ground bulk sediment samples with the CHN analyser. Carbonate content was calculated from the difference between total carbon and organic carbon contents. The relative standard deviations of carbonate, organic carbon and total nitrogen are 1 %, 7 % and 8 % in the case of duplicate analysis for carbonate, organic carbon and total nitrogen contents of 90 wt. %, 0.2 wt. % and 0.02 wt. %, respectively.

Biogenic silica, or opal content, was analysed using the sodium-carbonate leaching method modified from Mortlock and Froelich [22]. Approximately 2 to 5 mg of an aliquot sample was weighed into a 20 mL polypropylene vial. 1 mL 1N HCl solution was added to the vial to dissolve out carbonate, and then dried up at 40–50 °C. Then 1 mL 2 % H_2O_2 solution was added to remove organics, and again dried up at 40–50 °C. Exactly 10 mL 7 % Na_2CO_3 solution was added with a repipit to the vial, which was then capped and mixed well, sonified and placed in a constant-temperature water bath pre-heated to 85 °C. The sample was shaken vigorously every hour. After 6 h, the vial was removed from the bath. Residues of selected samples were examined under an optical microscope to verify complete dissolution of the siliceous micro-organisms. Several samples that gave unusual values were analysed three times, yielding a precision of ± 3 % of the measured values.

The contribution of lithogenic matter was calculated as follows: Lithogenic = Total - Carbonate - Opal - 1.8 × Corganic (= organic matter). Sediment aliquots for AMS ^{14}C dating were disaggregated, wet-sieved at 63 μm and picked for *Globorotalia tumida* which was analysed for the dating. *G. tumida*, a deep-dwelling planktonic foraminifer, was used because it is the only species consis-

Table I. Sampling dates, flux rates, percentages and various ratios (C/N, opal/Carbonate and Corg/Ccarbonate) of material collected at Site 1.

Sample number	Trap cup open - close	Duration days	Fluxes in mg m^{-2} day^{-1}					% of Total				C/N atom	Opal/ Carbonate wt.:wt.	Corg/ Ccarbonate atom
			Total	Carbonate	Organic matter	Biogenic opal	Lithogenics	Carbonate	Organic matter	Biogenic opal	Lithogenics			
Shallow trap														
1	4-Jun-91 - 15-Jun-91	12	139.0	55.0	15.3	32.1	36.6	39.5	11.0	23.1	26.3	8.1	0.58	1.29
2	16-Jun-91 - 30-Jun-91	15	151.2	87.1	10.8	31.8	21.6	57.6	7.1	21.0	14.3	8.2	0.37	0.57
3	1-Jul-91 - 15-Jul-91	15	135.0	70.2	15.8	30.4	18.5	52.0	11.7	22.5	13.7	7.5	0.43	1.04
4	16-Jul-91 - 31-Jul-91	16	116.1	57.9	11.0	22.4	24.7	49.9	9.5	19.3	21.3	8.0	0.39	0.88
5	1-Aug-91 - 15-Aug-91	15	127.8	79.2	10.9	22.9	14.8	62.0	8.5	17.9	11.6	7.2	0.29	0.63
6	16-Aug-91 - 31-Aug-91	16	218.7	127.8	21.5	53.9	15.6	58.4	9.8	24.6	7.1	7.6	0.42	0.77
7	1-Sep-91 - 15-Sep-91	15	180.3	84.0	20.1	38.9	37.4	46.6	11.1	21.6	20.7	7.4	0.46	1.10
8	16-Sep-91 - 30-Sep-91	15	294.2	119.4	36.0	87.1	51.7	40.6	12.2	29.6	17.6	8.2	0.73	1.39
9	1-Oct-91 - 15-Oct-91	15	198.6	80.1	24.4	43.2	50.8	40.3	12.3	21.8	25.6	7.2	0.54	1.40
10	16-Oct-91 - 31-Oct-91	16	138.1	49.4	14.4	20.5	53.8	35.8	10.4	14.8	39.0	7.9	0.41	1.34
11	1-Nov-91 - 15-Nov-91	15	132.1	58.2	11.4	22.4	40.1	44.1	8.6	16.9	30.4	6.4	0.38	0.90
12	16-Nov-91 - 30-Nov-91	15	155.0	74.7	15.0	35.5	29.8	48.2	9.7	22.9	19.2	7.8	0.47	0.92
13	1-Dec-91 - 15-Dec-91	15	137.8	64.4	12.6	30.0	30.9	46.7	9.1	21.7	22.4	7.3	0.47	0.90
14	16-Dec-91 - 31-Dec-91	16	252.1	120.3	28.8	56.8	46.2	47.7	11.4	22.5	18.3	8.1	0.47	1.10
15	1-Jan-92 - 15-Jan-92	15	217.5	94.6	20.6	48.5	53.8	43.5	9.4	22.3	24.7	7.0	0.51	1.00
16	16-Jan-92 - 31-Jan-92	16	256.1	83.8	26.1	95.3	51.0	32.7	10.2	37.2	19.9	7.8	1.14	1.43
17	1-Feb-92 - 15-Feb-92	15	124.5	63.7	11.5	25.0	24.2	51.2	9.2	20.1	19.5	7.1	0.39	0.83
18	16-Feb-92 - 15-Apr-92	60	96.0	30.9	11.6	39.4	14.1	32.1	12.1	41.1	14.7	8.2	1.28	1.73
Deep trap														
1	4-Jun-91 - 15-Jun-91	12	105.0	41.8	10.0	23.4	29.8	39.8	9.5	22.3	28.4	7.6	0.56	1.10
2	16-Jun-91 - 30-Jun-91	15	97.9	50.8	7.5	22.0	17.7	51.9	7.6	22.5	18.0	7.6	0.43	0.68
3	1-Jul-91 - 15-Jul-91	15	116.1	69.8	8.5	27.7	10.2	60.1	7.3	23.9	8.8	7.0	0.40	0.56
4	16-Jul-91 - 31-Jul-91	16	121.0	56.4	9.7	25.3	29.5	46.6	8.0	20.9	24.4	7.6	0.45	0.79
5	1-Aug-91 - 15-Aug-91	15	140.9	71.7	10.6	24.3	34.4	50.9	7.5	17.2	24.4	7.1	0.34	0.68
6	16-Aug-91 - 31-Aug-91	16	156.1	88.6	8.9	22.7	35.9	56.8	5.7	14.6	23.0	8.0	0.26	0.46
7	1-Sep-91 - 15-Sep-91	15	229.7	86.6	27.9	63.3	52.0	37.7	12.1	27.5	22.6	8.0	0.73	1.48
8	16-Sep-91 - 30-Sep-91	15	200.6	103.7	13.6	38.6	44.7	51.7	6.8	19.2	22.3	8.1	0.37	0.60
9	1-Oct-91 - 15-Oct-91	15	298.1	124.0	31.0	90.0	53.1	41.6	10.4	30.2	17.8	6.5	0.73	1.15
10	16-Oct-91 - 31-Oct-91	16	178.8	50.8	14.1	30.4	83.5	28.4	7.9	17.0	46.7	8.0	0.60	1.27
11	1-Nov-91 - 15-Nov-91	15	149.2	52.5	11.1	24.9	60.6	35.2	7.5	16.7	40.6	6.8	0.47	0.98
12	16-Nov-91 - 30-Nov-91	15	142.8	70.9	8.5	25.1	38.3	49.6	6.0	17.6	26.8	7.6	0.35	0.55
13	1-Dec-91 - 15-Dec-91	15	131.1	56.4	10.9	29.7	34.1	43.0	8.3	22.7	26.0	6.7	0.53	0.89
14	16-Dec-91 - 31-Dec-91	16	231.2	80.8	31.6	36.4	82.4	35.0	13.6	15.8	35.6	8.1	0.45	1.80
15	1-Jan-92 - 15-Jan-92	15	174.8	83.7	15.8	44.7	30.6	47.9	9.0	25.6	17.5	7.3	0.53	0.87
16	16-Jan-92 - 31-Jan-92	16	179.6	75.8	1412 .6	59.3	30.0	42.2	8.1	33.0	16.7	7.7	0.78	0.89
17	1-Feb-92 - 15-Feb-92	15	316.0	88.0	31.5	148.8	47.7	27.8	10.0	47.1	15.1	7.0	1.69	1.65
18	16-Feb-92 - 15-Apr-92	60	69.0	22.5	7.3	29.0	10.3	32.6	10.5	42.0	14.9	7.8	1.29	1.49

tently abundant enough for the analysis. The analyses were performed on four levels in the surface sediments in the Nuclear Sciences, New Zealand.

4. RESULTS

Records from two water depths at Site 1 are listed in *table I*. Annual mass fluxes were 57.10 and 53.83 g $m^{-2}yr^{-1}$ at 1592 m and 3902 m water depth, respectively (*table II*). Calcium carbonate ($CaCO_3$) was generally the major component of settling particles, followed by biogenic opal (silica). The amount of lithogenic matter was about twice that of particulate organic matter (POM). The average concentrations of $CaCO_3$, POM, opal, and lithogenic matter were 43.7 %, 10.6 %, 25.7 %, and 20.0 % at the shallow trap and 41.2 %, 9.1 %, 26.2 %, and 23.5 % at the deep trap, respectively.

Sinking particle fluxes showed seasonal variations. The period of sample collection can be divided into four periods based upon the total mass fluxes and the compositions: period 1 (May to July); period 2 (August to October); period 3 (November to the beginning of December); and period 4 (the end of December to April) (*figures 2* and *3*). Although there is a lack of data for May, period 1 is assumed to start in May because similar pictures were obtained on sea-surface current and temperature in May to July in 1991 based upon the data set provided by the Meteorological Institute of Japan. High total mass flux associated with a higher content of POM characterised periods 2 and 4, while low total mass fluxes were observed during periods 1 and 3.

The sinking particle flux pattern at the shallow depth was generally imprinted at the deep level with time-lags. For example, by comparing the "peak-valley" succession of fluxes within period 2, the penetration of total flux from 1592 m to 3902 m was shifted for one sampling period (about two weeks), which gives a sinking speed of about 160 m day^{-1}, a value consistent with previous results [10]. Furthermore, total mass flux determined at the shallow trap was higher than that measured at the deep trap. These findings indicate that vertical transport was a major process in the West Caroline Basin. It is compatible with no occurrence of turbidites in the sedimentary core retrieved from Site 1 [18].

Carbonate was the major constituent of the mass flux and consisted of coccolithophores/coccoliths, planktonic foraminiferal tests, and pteropod shells. In this paper, as presented in *table I*, we did not distinguish carbonates by origin. The annual carbonate flux observed at the shallow trap at Site 1 was about 13 % higher than that observed at the deep trap. Organic matter fluxes were higher during periods 2 and 3 than during the other periods. C/N atomic ratios of sinking particles were on average 7.3, showing no definite seasonal variations (*table II*).

The annual fluxes of biogenic opal at Site 1 were about 14 g $m^{-2}yr^{-1}$ at both depths. High opal fluxes were generally accompanied by peaks of total mass fluxes. Opal fluxes were sometimes higher at the deep trap than at the shallow trap in September to October and in February when carbonate and organic carbon fluxes showed similar patterns. It takes more time for sinking particles to reach the deeper trap through the water column. Therefore, the fluxes at the deep trap could reflect surface ocean conditions in a larger area due to lateral advection.

The mass fluxes of carbonate and biogenic opal are plotted against organic matter flux in *figure 4a*. Data from the shallow sediment trap only are presented here in order to avoid complications from degradation or from resuspension in the bottom water. These data indicate that biogenic opal and organic matter fluxes are strongly correlated (r = 0.83) as are carbonate and organic matter, but to a lesser extent (r = 0.75) (*figure 4a*). Samples with higher biogenic opal fluxes were associated with higher organic matter and carbonate fluxes and belonged to the field with a Corganic/Ccarbonate ratio >1 (*figure 4b*).

Table II. Seasonal variation of MARs of components to the deep Caroline Basin and their ratios.

Period	Trap	Total MAR (g/m^2)	Carbonate MAR		Organic matter MAR		Total nitrogen MAR		Biogenic Opal MAR		Lithogenic MAR		C/N atom	Corg/ Ccarb atom	Opal/ Carbonate wt./wt.
			(g/m^2)	(%)	(g/m^2)	(%)	(g/m^2)	(%)	(g/m^2)	(%)	(g/m^2)	(%)			
Site 1															
Spring	Shallow	12.55	5.81	46.3	1.28	10.2	0.10	0.8	2.77	22.1	2.68	21.4	7.57	1.02	0.48
	deep	9.98	4.63	46.4	0.86	8.6	0.07	0.7	2.23	22.3	2.26	22.7	7.11	0.85	0.48
Summer	Shallow	17.72	8.28	46.7	1.94	11.0	0.16	0.9	4.07	23.0	3.43	19.4	7.25	1.09	0.49
	deep	18.40	8.02	43.6	1.61	8.8	0.14	0.8	4.09	22.2	4.67	25.4	7.05	0.93	0.51
Autumn	Shallow	6.37	2.96	46.4	0.58	9.2	0.05	0.8	1.32	20.7	1.51	23.7	6.77	0.91	0.44
	deep	6.35	2.70	42.5	0.46	7.2	0.04	0.7	1.20	18.8	2.00	31.5	6.60	0.79	0.44
Winter	Shallow	20.46	7.95	38.9	2.23	10.9	0.18	0.9	6.49	31.7	3.78	18.5	7.41	1.30	0.82
	deep	19.11	6.77	35.4	1.99	10.4	0.17	0.9	6.61	34.6	3.74	19.6	7.17	1.36	0.98
Total	Shallow	57.10	25.00	43.7	6.04	10.6	0.51	0.9	14.65	25.7	11.41	20.0	7.32	1.12	0.59
annual	deep	53.83	22.12	41.2	4.92	9.1	0.43	0.8	14.12	26.2	12.67	23.5	7.06	1.03	0.64

Spring: May-July ; Summer: August-October; Autumn: November-15 December; Winter: 16 December-April.

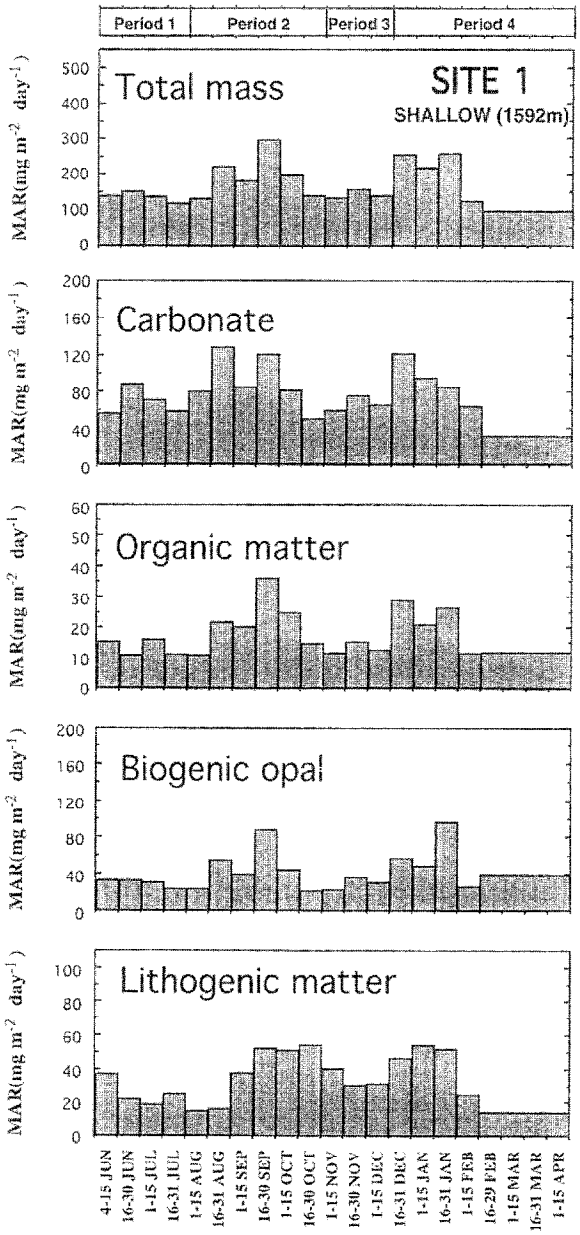

Figure 2. Fluxes of total mass, carbonate, organic matter, biogenic opal, and lithogenic matter from June 1991 to March 1992 at the shallow trap of Site 1.

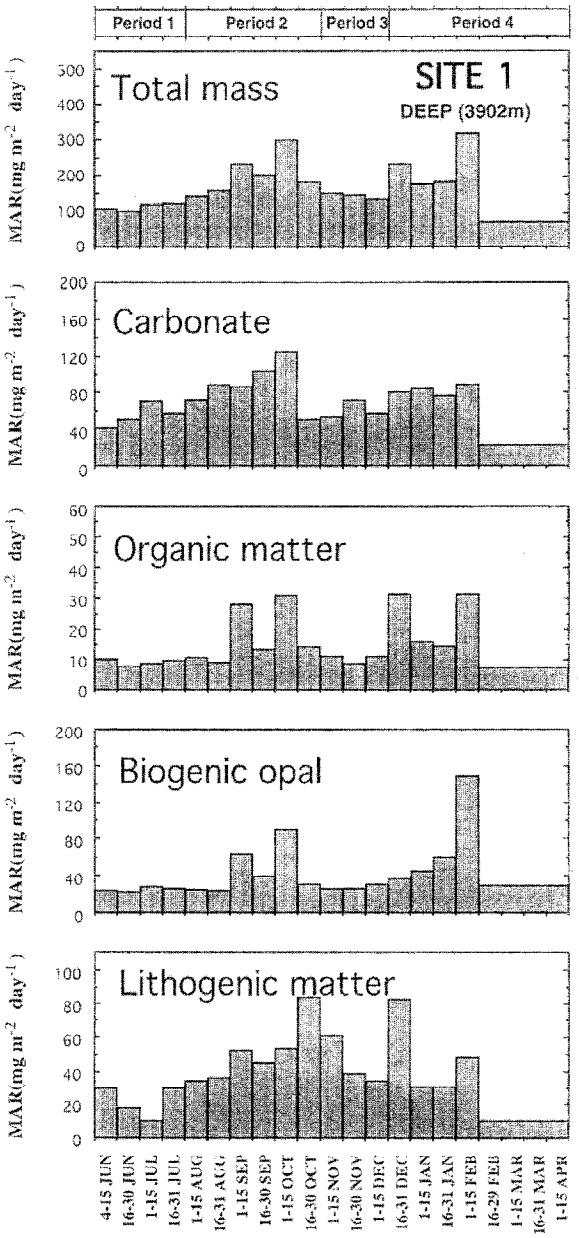

Figure 3. Fluxes of total mass, carbonate, organic matter, biogenic opal, and lithogenic matter from June 1991 to March 1992 at the deep trap of Site 1.

At the shallow trap, the annual lithogenic flux at Site 1 was 11.4 g $m^{-2}yr^{-1}$. The lithogenic matter was largely composed of clay minerals. Volcanic ash was only a minor contributor. High lithogenic fluxes were accompanied with high total mass fluxes as was observed for opal fluxes (*figures 2* and *3*).

Radiocarbon ages obtained on *Globorotalia tumida* in the surface sediments at Site 1 were 1041 ± 62, 6361 ± 73, 7660 ± 81 and 11588 ± 89 yr.B.P. at the subbottom depth of 0–1 cm, 7–9 cm, 15–17 cm and 23–25 cm, respectively. These results give a linear sedimentation rate of 2.26 cm kyr^{-1} in the surface sediments. Based upon smear

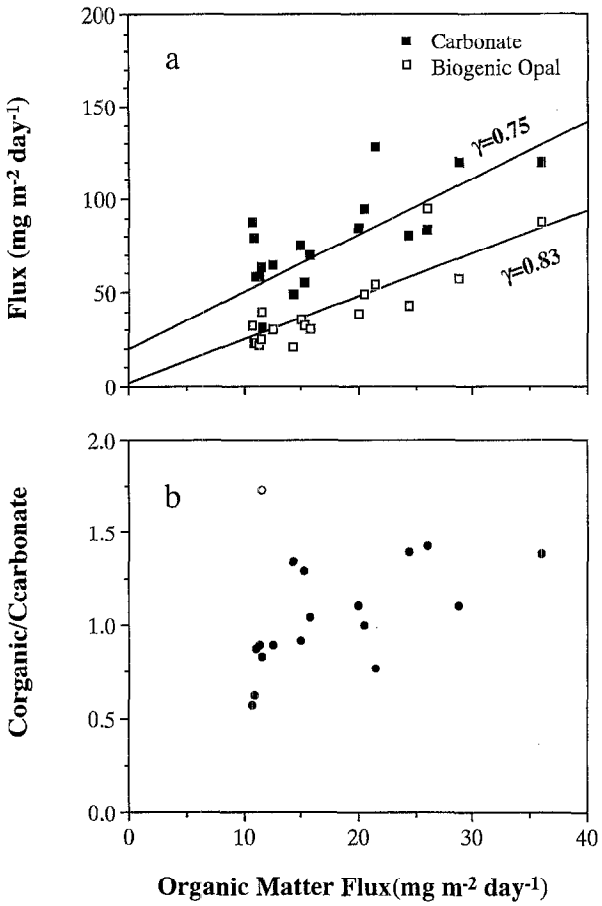

Figure 4. Biogenic opal ( ) and carbonate fluxes (■) (a) and carbon rain ratios (●,○) (b) versus organic matter flux from the shallow trap at Site 1. Open circle represents a sample taken for two months (from February 16 to April 15) while solid circles represent samples collected for a half month.

slide examination and soft X-ray analysis, neither graded-bedding nor cross-lamination was observed in a 35 cm thick layer of surface sediments. One to three millimetre-thick surface sediments were served for chemical analysis. The contents of carbonate carbon, organic carbon, total nitrogen, biogenic opal and lithogenic matter were 0.16, 0.80, 0.13, 15.72 and 81.51 wt.%, respectively. Their mass accumulation rates (MARs) were 0.0155, 0.0777, 0.0119, 1.53 and 7.92 $gm^{-2}yr^{-1}$, respectively. MARs (mg $cm^{-2}kyr^{-1}$) were calculated by multiplying the linear sedimentation rate (cm kyr^{-1}) by dry bulk density (0.43g cm^{-3}) to give the bulk MAR (g $cm^{-2}kyr^{-1}$) and then by the content of each component to give its mass accumulation rate.

5. DISCUSSION

5.1. General characteristics of particle fluxes in the West Caroline Basin

Annual mass flux at the shallow trap at Site 1 is 57.10 g $m^{-2}yr^{-1}$. Sediment trap experiments in the eastern part of the West Caroline Basin (5° N, 139 °E) and the Philippine Basin (12° N, 134° E) gave annual fluxes of 6.57 g $m^{-2}yr^{-1}$ and 1.73 g $m^{-2}yr^{-1}$ at water depths of 1130 m and 1200 m, respectively [19]. Such north-eastward decreasing fluxes reflect the steep gradients of primary productivity. Comparison of annual fluxes in the equatorial region of the Pacific Ocean shows that the annual fluxes in the West Caroline Basin were less than that (124.7 g $m^{-2}yr^{-1}$) observed at a water depth of 1268 m in the Panama Basin of the eastern equatorial Pacific (5° N, 86° W) [12] and comparable to those (21.77 g $m^{-2}yr^{-1}$ at a water depth of 3495 m in 1983 and 41.74 g $m^{-2}yr^{-1}$ at a water depth of 2908 m in 1984 at 1° N, 139° W; 22.3 to 34.8 g $m^{-2}yr^{-1}$ at water depths between 2200 and 3618 m at 5° S to 5° N, 140° W) observed in the middle part of the equatorial Pacific [6, 13]. This is also ascribed to the general trend of primary productivity gradients, which decrease gradually from east to west between 80° W and 170° E and from west to east between 130° E and 150° E [20].

Positive correlation between the mass flux and the organic matter indicated that sedimentation of particles was linked to biological processes in the surface sea water. Whereas the important autotrophs found in the samples during periods 1 and 3 were coccolithophorids, which might have provided mucus for the agglutination of mineral particles and biogenic hardparts, diatoms were dominant during periods 2 and 4. Coccolithophorids are well known to form aggregates with nonbiogenic particles and accelerate the sinking speed of small particles. Besides, the incorporation of lithogenic particles into organic aggregates forms high-density particles with faster sinking speed, which prevents the degradation of organic matter through the water column [7, 15]. As mentioned before, the sinking speeds of total mass could be evaluated by examining flux maxima of 1592 m and 3902 m data. In September and October, one sampling lag time was observed between the two depths, which gave a mean sinking speed of around 160 m day^{-1} (*figures 2* and *3*). This is compatible with the sinking speeds of diatoms of 175 m day^{-1} [28].

Generally, higher fluxes of organic matter are associated with higher activities of biogenic opal- and carbonate-producing plankton communities (*figure 4a*). As the

organic matter content increases, the organic carbon/carbonate carbon ratio shows a tendency to increase (*figure 4b*). Carbonate-producing plankton is predominant during periods 1 and 3. *Figure* 5 shows water temperature, fluorescence (an indicator for chlorophyll *a*), and nutrient concentration profiles obtained during period 1 in 1991 and 1992 at Site 1 and nearby. The results indicate that chlorophyll *a*, a representative index of phytoplankton, has a large peak at a depth of 74 m and is completely depleted below 200 m.

Phosphate and silica profiles with detailed sampling of the upper 300 m were depleted in surface waters with its more stratified surface waters during period 1. These concentrations changed near the thermocline, present around 170 m depth, where the silica/phosphate (SiO_2/PO_4) atomic ratios increased rapidly from 2 to 19. High primary productivity in association with predominance of diatoms characterises the northern part of the western Pacific, whose surface water shows silica/phosphate atomic ratios of more than 15. It implies a high input of silica into the surface water for sustaining siliceous plankton communities. These lines of evidence suggest that limited silica supply to the euphotic zone at site 1 could be responsible for the inhibition of growth of siliceous plankton, and thus help in the development of calcareous plankton.

5.2. Comparison of mass accumulation rates between sediment traps and surface sediments

The deep trap was deployed at about 3902 m water depth, which is about 500 m above the sea floor at Site 1. If we

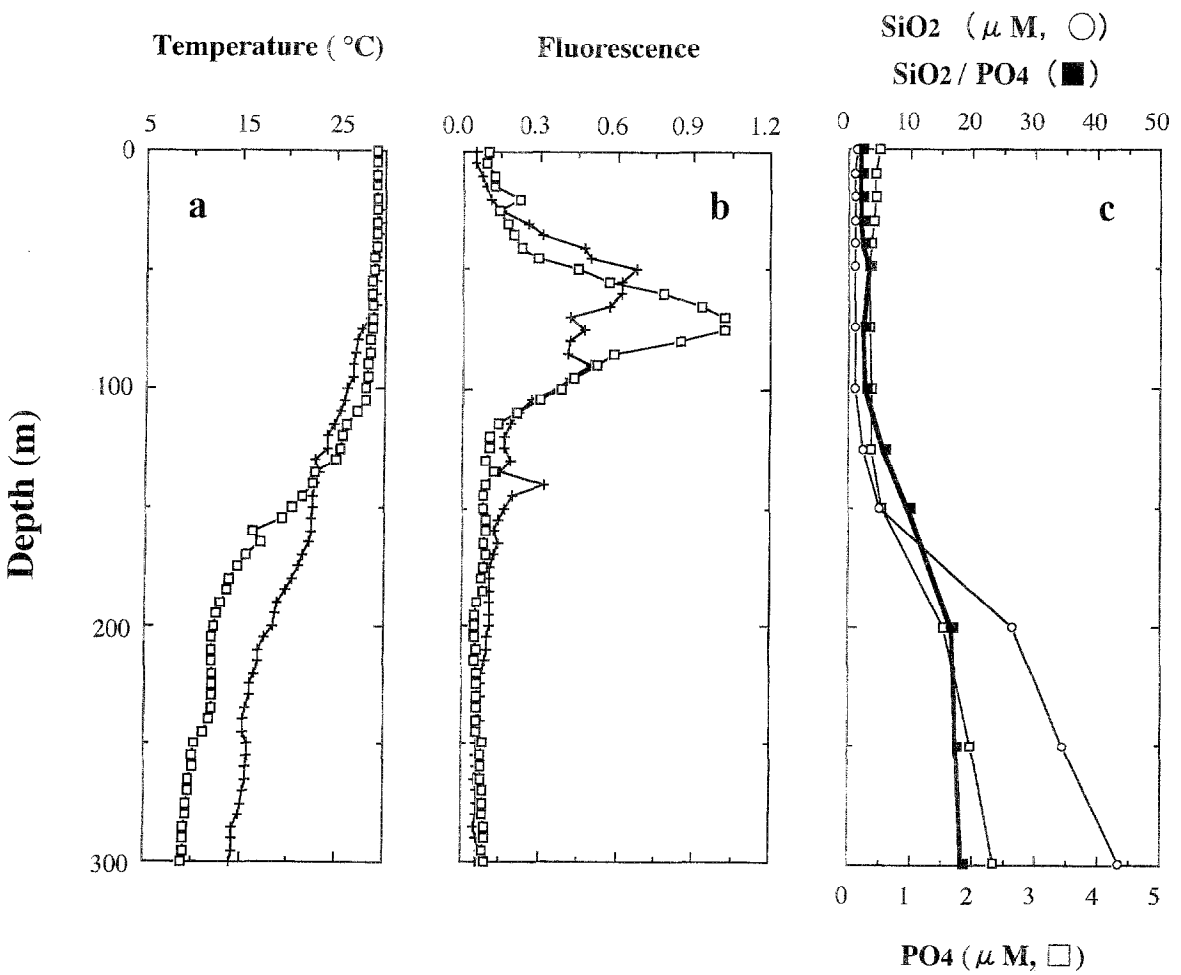

Figure 5. Temperature, fluorescence (indirect indicator for total chlorophyll a), dissolved silica and phosphate concentrations, and dissolved silica/dissolved phosphate ratio versus depth in the surface water at Site 1 during period 1. (+: obtained during May , 1991 at Site 1 (2° 59.8' N, 135° 201.5' E). □, ■, ●: obtained during May, 1992 nearby (4° 07.5' N, 136° 16.6' E).

consider the sinking speed of 160 m day^{-1}, the loss of material during sinking is expected to be small. So we assumed that the sinking flux at the deep trap was not significantly different from the amount reaching the sea floor. The amount of biogenic components collected in the sediment traps and their accumulation in surface sediments at trap sites can be compared for primary productivity values which were taken from the latest productivity map made by Berger et al. [3] (*table III*). Nitrogen fixation was calculated using the Redfield ratio [26].

Accumulation rates of biogenic components measured in the sediment traps were higher than those of surface sediments at the trap site. The difference was largest for carbonate, which was 99 % less in the surface sediments compared to that in the shallow sediment traps. Carbonate was partly dissolved during vertical transport through the water column, 12 % less in the deep trap compared to that in the shallow trap. This carbonate dissolution is attributed to the reaction of sinking particles with undersaturated deep sea water. The dissolution was accelerated below the lysocline depth of about 3500 m in the Caroline Basin. The sea floor at 4414 m at Site 1 was located just above the CCD (Carbonate compensation depth) of about 4500 m. The continuous reaction of settling particles with bottom sea water on the sea floor for long time periods diminished the concentration of carbonate in the surface sediments.

Biogenic opal was about 90 % less in surface sediments compared to that in sediment traps. The ocean at all depths is undersaturated for biogenic opal, but the amount preserved may be proportional to the opal rain rate [4]. Long-term interaction between opal and sea water depleted the opal content. The sedimentation rate is an especially important factor in controlling the burial rate of biogenic opal in surface sediments. Various studies have shown that only a small fraction of the biogenic opal reaching the sediment-water interface is buried in the sediments [5, 24].

About 20 % of the organic matter was decomposed between the shallow and deep sediment traps and more than 98 % between the deep sediment trap and final burial in the surface sediments. The relative amount of organic carbon preserved in surface sediments was about 0.10 % of primary productivity. This is in the range of data obtained in the Arabian Sea (0.10 %, [8]) and in the northern North Pacific (0.008 %, [9]). These results confirm that the sediment-water interface is a major site of degradation and dissolution processes of organic matter [5, 12]. Since the sea floor at Site 1 was below the lysocline, the dissolution of carbonate could have reduced the sealing effect by carbonate, and thus accelerated the degradation rate of organic matter. Nitrogen accumulation rates revealed preservation levels similar to those of organic carbon. The variation of the organic carbon/total nitrogen ratio was not significant at the sediment-water interface. This suggests that inorganic nitrogen which is a byproduct of organic matter during early diagenesis may be fixed into the sediments by replacing alkaline ion sites in the clay minerals and/or by adsorption onto sedimentary particles.

5.3. The correlation between particle fluxes and wind speed and its implications for paleoceanography

Climate and hydrography are often reflected in the amount of sinking particle fluxes to the deep ocean [8, 15, 23]. *Figure 6* presents sinking particle fluxes at Site 1 as well as wind speed and wind direction versus months in 1991–1992 at Koror, Palau Island (7° N, 135° E), the nearest land-based meteorological station. West wind was stable from June to November and east wind from December to May. High wind speed observed in August–

Table III. Comparison of fluxes of total mass, carbonate carbon, organic carbon, total nitrogen, biogenic opal, and lithogenic matter in primary produced matter with accumulation rates measured in sediment traps and surface sediments.

	Total mass flux		Carbonate carbon		Organic carbon		Total nitrogen		Corg/N molar ratio	Biogenic opal		Lithogenic matter	
	$gm^{-2}y^{-1}$	%	$gm^{-2}y^{-1}$	%	$gm^{-2}y^{-1}$	% (1)	$gm^{-2}y^{-1}$	% (2)		$gm^{-2}y^{-1}$	%	$gm^{-2}y^{-1}$	%
Primary productivity					80.0	100	14.06	100	6.6				
Site 1, Trap (1592m)	57.10	100	3.0	100	3.4	4.2	0.51	3.6	7.7	14.7	100	11.4	100
Site 1, Trap (3902m)	53.83	94	2.7	88 (2)	2.7	3.4	0.43	3.0	7.5	14.1	96	12.7	111
Site 1, Sediments (4402m)	9.72	17	0.0155	0.52	0.078	0.10	0.0119	0.08	7.6	1.5	10	7.9	69

(1) Primary production values are taken from Berger et al. [3].
(2) Nitrogen fixation was calculated using the Redfield ratio [26].

September and December–February was accompanied with high total mass fluxes at Site 1.

Recent sediment trap experiments in the Arabian Sea showed surface cooling and a deeper mixing of the upper ocean with increasing wind speed [8]. Nutrient input into the euphotic zone associated with this process triggers primary productivity. In addition, the linkage of biogenic activity with a high supply of lithogenic matter increases the efficiency of the organic carbon pump. Another process that stimulates primary production with increasing wind speed is upwelling. Biological study shows that silica-producing planktonic communities live with high nutrient concentration in the centre of upwelling while carbonate-producing communities surround them. The Corganic/Ccarbonate ratio of sinking particles has been suggested as an indicator of surface ocean fertility with increasing ratios reflecting a more efficient organic carbon pump [1]. The opal/carbonate and Corganic/Ccarbonate ratios of sinking particles showed the surface sea water was more nutrient-rich at Site 1 during periods 2 and 4 than during periods 1 and 3 (*figure 6*). However, peak fluxes and high carbon rain ratios during period 2 appeared to be delayed with respect to the maximum wind speed. In period 4, flux peaks and wind speed maxima coincided, but higher carbon rain ratios occurred somewhat later towards the end of period 4.

Sea-surface current data provided by the Meteorological Institute of Japan indicate strong eastward currents around

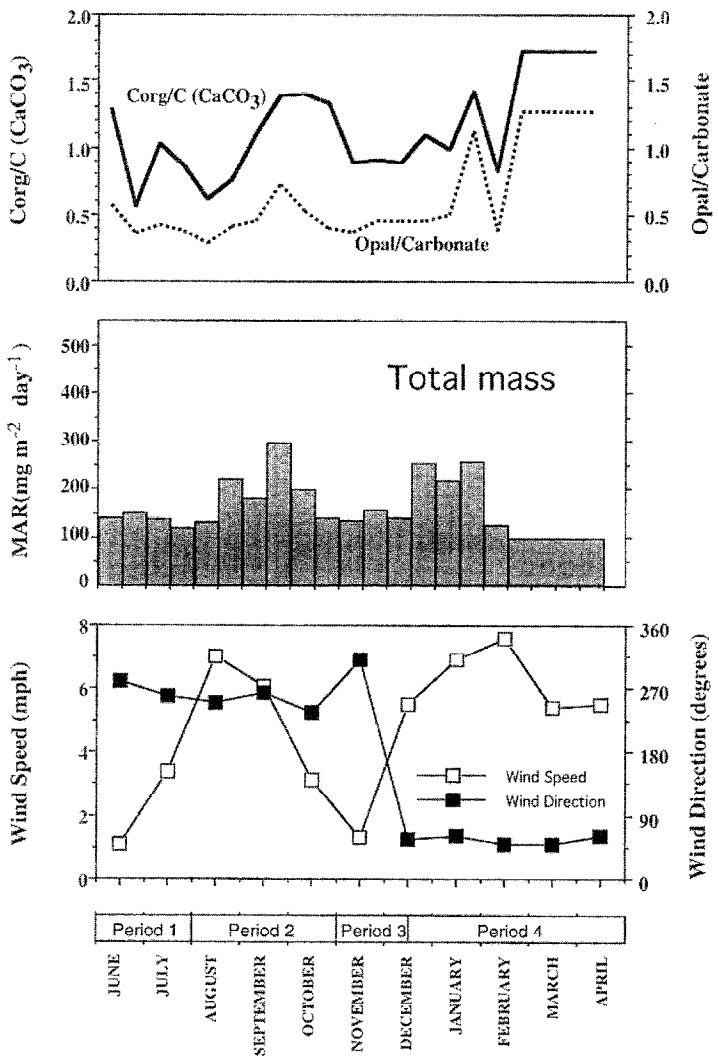

Figure 6. Organic carbon/carbonate carbon and opal/carbonate ratios (a) and total flux (b) at the shallow trap of Site 1 and monthly variation of wind speed and wind direction (c) at Koror, Palau Island from June 1991 through May.

Site 1, which could supply nutrients from the coastal area off the Philippine and Maluk Islands to the trap site. The water mass should be enriched in land-derived lithogenic matter and its incorporation into fecal pellets or marine snow raises the lithogenic flux. This is supported by the observation of high mass accumulation rate of lithogenic matter at Site 1 during periods 2 and 4. Higher Corganic/Ccarbonate ratios of sinking particles with higher opal/carbonate ratio characterised the effective biological pump during these periods (*table I* and *figure 6*).

The equatorial upwelling area plays an important role in the discussion about the causes of glacial-interglacial climatic and atmospheric CO_2 changes. Much evidence of productivity increase during the last glacial maximum has been gathered for the eastern equatorial Pacific [21, 25]. In the western equatorial Pacific, the accumulation of organic carbon was mainly controlled by primary productivity. Paleoproductivity estimates calculated by using the formula of Sarnthein et al. [27] are considered to be the most reliable, because the fluctuating pattern correlated closely with changes in the accumulation rate of biogenic opal in core sediments taken just at Site 1 [17]. The primary productivity in the West Caroline Basin showed an increase during Stage 8, Stage 7/6 boundary, late Stage 6, Stage 3, and Stage 2. The results from sediment trap experiments imply that the biological pump is effective with high activities of opal-producing planktonic community, and that during the glacial stages the biological pump was effectively removing carbon from the surface water in the equatorial area of the West Pacific Ocean.

6. SUMMARY AND CONCLUSIONS

We present time-series data on fluxes of sinking particles from the West Caroline Basin in the equatorial western Pacific. The following points summarise the data interpretation:

1. Annual mass flux at the shallow trap at Site 1 was 57.10 g $m^{-2}yr^{-1}$. Generally, higher fluxes of organic matter were associated with higher activities of biogenic opal- and carbonate-producing plankton communities. As the organic matter content increases, the organic carbon/carbonate carbon ratio shows a tendency to increase. Carbonate-producing plankton is predominant during periods 1 and 3, which could be due to limited silica supply to the euphotic zone.

2. The amount of biogenic components collected in the sediment traps and their accumulation in surface sediments at Site 1 could be compared in terms of primary productivity values. Carbonate flux was 99 % less in the surface sediments compared to the shallow sediment trap, due to the reaction with undersaturated deep sea water on the sea floor, rather than during sinking through the water column. Biogenic opal was about 90 % less in surface sediments than in the shallow sediment trap. About 20 % of the organic matter was decomposed between the shallow and deep sediment traps, and more than 98 % between the deep trap and final burial in the bottom sediments. The relative amount of organic carbon preserved in surface sediments was about 0.10 % of primary productivity.

3. Based on the opal/carbonate and Corganic/Ccarbonate ratios of sinking particles, surface sea water was more nutrient-rich during periods 2 and 4 at Site 1. These high total mass fluxes could be stimulated by wind.

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