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DISTRIBUTION OF PARTICULATE MATTER WITH SPECIAL REFERENCE TO BIOGENIC SILICA OF SURFACE WATERS IN THE BERING SEA GYRE IN SUMMER 1991

Akihiro SHIOMOTO and Miki OGURA

National Research Institute of Far Seas Fisheries, 7–1, Orido 5-chome, Shimizu 424

Abstract: Biogenic silica (BSi), lithogenic silica (LSi), particulate organic carbon (POC) and nitrogen (PON), and chlorophyll *a* (Chl. *a*) of surface waters were measured in the Bering Sea Gyre in summer. Twenty one stations were divided into three water types according to salinity and LSi distributions: the waters of the eastern Bering Sea Shelf (Type I), the waters around the Aleutian Islands (Type II), and other water types (Type III). The mean concentrations of particulate matter were largest in Type II and smallest in Type I. The concentration of BSi in Type II was 22 times larger than that in Type I, and those of other components were several times larger in the former water type than in the latter type. The mean value of BSi/POC ratio was 0.02 in Type I, 0.28 in Type II and 0.15 in Type III, although the POC/PON ratios were nearly constant among water types (mean±SD=6.8±1.6). Furthermore, the mean value of BSi/POC ratio in Type II was twice as high as the typical Si (cellular silicon)/C (cellular carbon) ratio of diatoms (0.13) and was nearly equal to high values (0.30–0.65) in the Antarctic Ocean, possibly reflecting the high silicate demand of diatoms. These results show that BSi characterizes the distribution pattern of particulate organic matter, in particular, the diatoms, in surface waters of the polar seas.

1. Introduction

The Bering Sea is one of the more eutrophic and high primary productive marginal seas (TANIGUCHI, 1969; TAGUCHI, 1972; MCROY and GOERING, 1974; SAINO, 1979). Diatoms are known to be the predominant organism contributing to the high primary productivity in the sea (MOTODA and MINODA, 1974). Marginal areas and frontal areas of the Antarctic Ocean are also highly productive seas, dominated by diatoms. In the Antarctic Ocean, molar ratios of biogenic silica (BSi) to particulate organic carbon (POC) of the surface waters are as high as 0.30–0.65 (SMITH and NELSON, 1985; NELSON and SMITH, 1986; NELSON *et al.*, 1989; TRÉGUER *et al.*, 1990). The ratios are several times higher than the typical Si (cellular silicon)/C (cellular carbon) ratio for culture diatoms (mean±95% CI; 0.13±0.04) reported by BRZEZINSKI (1985). This is the chemical character of Si-rich particulate organic matter of the Antarctic waters. Therefore it is possible that particulate organic matter in the Bering Sea, northern subpolar sea, is also siliceous. BANAHAN and GOERING (1986) reported the distribution of BSi and BSi/POC ratio (0.16) over the eastern Bering Sea Shelf, although a

Si-rich environment was not found. In this paper, we present the surface distributions of particulate matter, with special reference to the density of biogenic silica in the Bering Sea Gyre in summer.

2. Materials and Methods

Water sampling was carried out during a cruise of the T/S SHIN-RIASU MARU, Miyako Fisheries High School, Iwate Prefecture, Japan, from June 10 to July 21, 1991 (Fig. 1). Seawater samples were collected from the surface with a plastic bucket at around noontime. For analyses of biogenic silica (BSi) and lithogenic silica (LSi), 0.5 *l* of seawater was filtered immediately after collection through 47 mm Nuclepore membranes (0.6 μm pore size). For analyses of particulate organic carbon (POC) and nitrogen (PON), 1 *l* of seawater was filtered through a 47 mm Whatman GF/F filter (precombusted at 400°C for 4 h). For analyses of chlorophyll *a* (Chl. *a*), 0.5 *l* of seawater was filtered through a 47 mm Whatman GF/F filter. All filters were stored at −20°C until analysis in a land laboratory.

The BSi abundance was obtained using the NaOH digestion method of PAASCHE (1973). The LSi remaining on the filter was extracted with 2.5 mol l^{-1} HF for 48 h (EGGIMAN and BETZER, 1976). Each filter for POC and PON determinations was dried in a vacuum desiccator after elimination of inorganic carbon remaining on the GF/F filter by fuming with HCl. POC and PON concentrations were measured simultaneously using a Yanagimoto Model MT-5

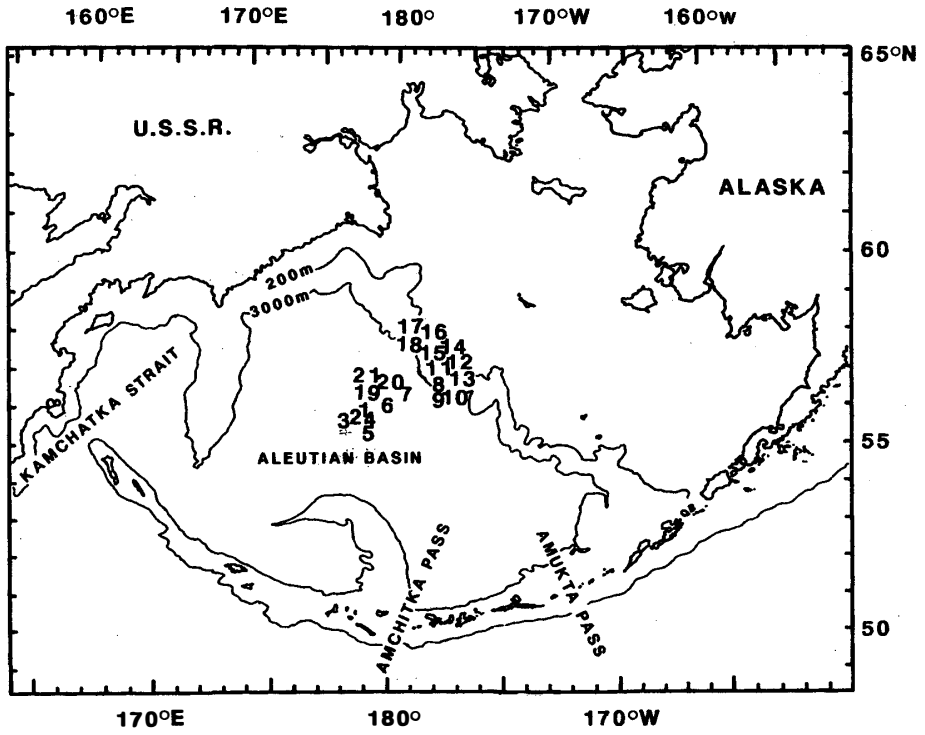

Fig. 1. Location of sampling stations in the Bering Sea Gyre in summer 1991.

CHN corder. Chl. *a* was determined by the fluorometric method with a Turner Model 1102, after extraction of phytopigments by 90% acetone (SATO *et al.*, 1981).

Temperature was measured immediately after the sampling of water. Salinity was determined with an Auto-Lab salinometer. Nutrients were measured according to the method of PARSONS *et al.* (1984). Water samples for nutrient determination were deep-frozen until measurement.

3. Result and Discussion

Waters less saline than 32.6 were observed at Stns. 11, 12, 13, 14 and 15 (Fig. 2). These stations were located on the continental slope of the eastern Bering Sea Shelf (Fig. 1) with low salinity water affected by the coastal waters. Concentrations of LSi at Stns. 4, 7, 10 and 20 (>0.25 μmol l^{-1}) were larger than those at other stations (Fig. 2). The approximate location of these stations was in the northern area of Amchitoka Pass (Fig. 1), through which the Alaskan Stream flows into the Bering Sea (OHTANI, 1970). The LSi-rich waters were affected by the neritic waters around the Aleutian Islands. According to salinity and LSi distributions of the present study area, sampling stations were divided into those located in three water types: the waters of the eastern Bering Sea Shelf (Type I), the waters of the Aleutian Islands (Type II), and other water types (Type III).

Concentrations of nutrients, particulate matter and Chl. *a* are summarized in Table 1. The mean values of all components were largest in Type II and smallest in Type I. The mean value of BSi in Type II was 22 times larger than that in Type I, although the mean values of nutrients, other particulate matter and Chl. *a* in the former water type were several times larger than those in the latter type.

A spring bloom of diatoms occurred in April to May over the eastern Bering

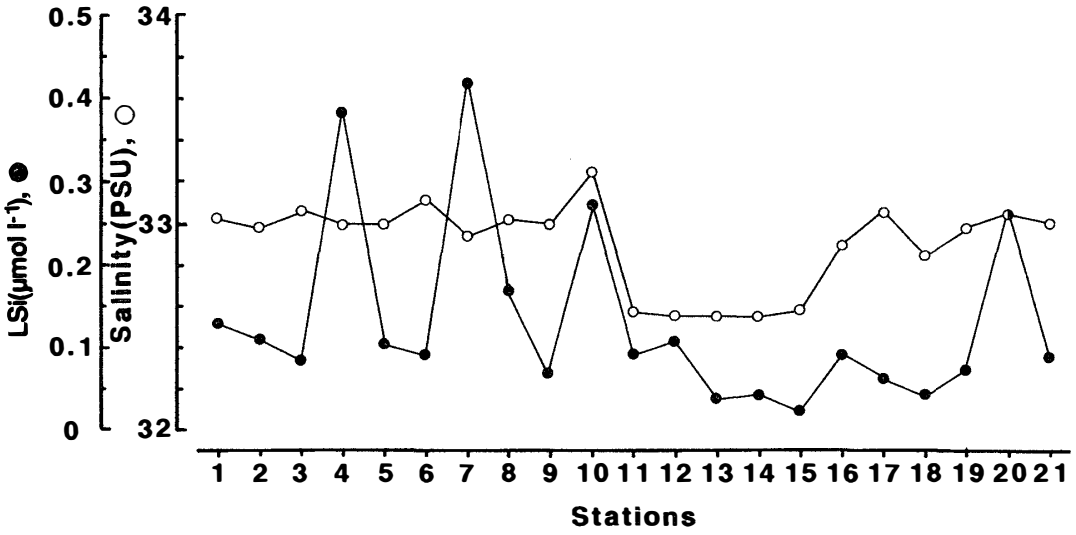

Fig. 2. Variabilities of salinity and lithogenic silica (LSi) concentration of surface waters in the Bering Sea Gyre in summer 1991. Open circles and solid circles indicate salinity and LSi, respectively.

Table 1. Location of sampling stations, water temperature, salinity, and concentrations of nutrients, particulate matter and Chl. a of surface waters in the Bering Sea Gyre in summer 1991.

	Stns.	Lat.	Long.	Temp. °C	Sal.	SiO_2	NO_2+NO_3	PO_4	BSi	LSi	POC	PON	Chl.*a*
						μmol l^{-1}			μmol l^{-1}				μg l^{-1}
Type I	11	56°49.78′N	177°13.56′W	7.1	32.578	4.4	3.4	0.67	0.73	0.095	20.2	2.25	0.18
	12	56°57.98′N	177°05.63′W	7.3	32.555	2.0	2.6	0.27	0.62	0.109	ND	ND	0.41
	13	56°56.12′N	176°57.22′W	7.3	32.563	ND	ND	ND	0.35	0.038	27.1	3.4	0.40
	14	57°21.94′N	177°05.04′W	7.4	32.563	3.7	3.3	0.56	0.23	0.045	27.9	2.76	0.20
	15	57°29.45′N	177°14.55′W	7.7	32.592	2.6	2.9	0.57	0.25	0.024	17.8	2.98	0.18
					mean	3.2	3.1	0.52	0.44	0.062	23.3	2.85	0.27
					±SD	±1.1	±0.4	±0.17	±0.23	±0.037	± 5.0	±0.49	±0.12
Type II	4	55°46.93′N	178° 39.85′E	5.7	33.003	20.2	7.2	1.13	8.87	0.386	38.1	9.50	1.32
	7	56°15.43′N	179°17.25′W	6.1	32.945	17.2	13.8	1.42	11.95	0.421	34.6	5.59	0.75
	10	56°13.31′N	177°15.14′W	6.9	33.249	19.4	11.3	0.75	10.75	0.276	31.1	3.64	0.64
	20	56°12.39′N	179° 25.23′E	7.2	33.027	22.3	16.4	1.73	6.65	0.264	36.4	5.82	1.39
					mean	19.8	12.2	1.26	9.56	0.337	35.1	6.14	1.03
					±SD	±2.1	±3.9	±0.42	±2.31	±0.079	±3.0	±2.40	±0.38
Type III	1	55°52.27′N	178°54.49′E	5.5	33.044	19.5	4.5	1.09	9.46	0.132	35.8	5.42	1.23
	2	55°46.47′N	178°22.22′E	5.8	32.989	19.2	8.4	1.30	3.44	0.109	19.5	2.49	0.72
	3	55°46.31′N	177°57.24′E	6.1	33.066	22.3	9.0	1.18	1.12	0.087	24.7	2.94	0.93
	5	55°47.00′N	178°49.80′E	6.2	33.014	13.6	5.8	1.01	3.12	0.105	25.5	3.83	0.46
	6	56°06.26′N	179°51.65′E	6.0	33.123	24.2	15.1	1.56	3.14	0.093	25.2	3.96	0.63
	8	56°24.95′N	177°26.45′W	7.0	33.026	7.8	5.2	0.86	7.64	0.171	26.1	3.79	0.71
	9	56°12.39′N	179°25.23′W	7.2	32.996	21.4	14.5	1.35	2.19	0.071	22.1	2.72	0.37
	16	57°37.38′N	177°37.29′W	7.6	32.915	1.9	9.1	1.15	5.42	0.093	26.0	4.15	0.49
	17	57°41.80′N	178°22.45′W	7.8	33.060	ND	ND	ND	0.69	0.067	28.6	4.94	0.55
	18	57°31.28′N	178°37.11′W	8.1	32.847	1.9	3.3	0.38	0.51	0.043	21.8	7.04	0.31
	19	56°00.04′N	178°50.49′E	7.1	32.981	27.7	17.6	1.18	4.09	0.074	32.8	5.08	1.14
	21	56°35.41′N	178°52.22′E	7.3	33.001	9.9	8.0	1.20	9.28	0.091	35.2	5.74	1.15
					mean	15.4	9.1	1.11	4.18	0.095	26.9	4.34	0.72
					±SD	± 8.9	±4.7	±0.30	±3.15	±0.033	±5.2	±1.35	±0.32

ND : No data

Sea Shelf (McROY and GOERING, 1974; SAMBROTTO *et al.*, 1986). Nutrients were exhausted by phytolankton populations and subsequently Chl. *a* decreased rapidly after the bloom (SAMBROTTO *et al.*, 1986). The present observations seem to have been made after the bloom event. Therefore particulate organic matter, especially BSi, and nutrients should have been low in Type I. This might partly be supported by the relative nutrient composition, SiO_2 : NO_2+NO_3 : PO_4, which was 6.2 : 6.0 : 1 in Type I, 15.7 : 9.7 : 1 in Type II and 13.9 : 8.2 : 1 in Type III. The abundance of SiO_2 in Type I was relatively less than those of other nutrients, showing that nutrient consumption by diatoms was selective. In contrast, no marked decrease of nutrients or particulate matter was observed in Type II, probably because of the continuous supply of nutrient-rich neritic waters

Table 2. Molar ratios of BSi/POC and POC/PON and the percent composition of BSi to total particulate silica (BSi + LSi) of surface waters in the Bering Sea Gyre in summer 1991.

	Stns.	BSi/POC	POC/PON	BSi/BSi+LSi
		molar ratio		%
Type I	11	0.04	9.0	88
	12	ND	ND	85
	13	0.01	7.9	90
	14	0.01	10.1	84
	15	0.01	6.0	91
	mean	0.02	8.3	88
	±SD	±0.02	±1.7	± 3.0
Type II	4	0.23	4.0	96
	7	0.35	6.2	97
	10	0.35	8.5	97
	20	0.18	6.3	96
	mean	0.28	6.3	97
	±SD	±0.09	±1.8	± 0.6
Type III	1	0.26	6.6	99
	2	0.18	7.8	97
	3	0.05	8.4	93
	5	0.12	6.7	97
	6	0.12	6.4	97
	8	0.29	6.9	98
	9	0.10	8.1	97
	16	0.21	6.3	98
	17	0.02	5.8	91
	18	0.02	3.1	92
	19	0.12	6.5	99
	21	0.26	6.1	99
	mean	0.15	6.6	96
	±SD	±0.09	±1.4	± 2.8

ND : No data

from the area around the Aleutian Islands.

Molar ratios of BSi/POC and POC/PON, and the percentage composition of BSi to total particulate silica (BSi/BSi+LSi), are summarized in Table 2. The mean BSi/POC ratio was 0.02 in Type I, 0.28 in Type II and 0.15 in Type III. The mean BSi/POC ratio in Type II was 14 times larger than that in Type I. The distribution pattern of this ratio is similar to those of particulate matter and nutrients; high BSi/POC ratio corresponds to high particle and nutrient concentrations. In contrast, the mean POC/PON ratio was 8.3 in Type I and about 6.5 in Types II and III. Although the mean value in Type I was slightly larger than those in Type II and III, the ratios were almost equal to the Redfield ratio (6.6) (REDFIELD *et al.*, 1963). The mean percentage of BSi to BSi+LSi was 88% in Type I, and about 97% in other water types. BSi was the dominant component of particulate silica of the surface waters in the Bering Sea Gyre in summer. These results indicate that BSi characterizes the distribution pattern of particulate organic matter of surface waters in the Bering Sea Gyre in summer.

Based on the typical Si/C ratio of cultured diatoms of 0.13±0.04 (BRZEZINSKI, 1985), the mean BSi/POC ratio in Type I (0.02) was significantly lower than the typical diatom ratio. The mean BSi/POC ratio in Type III (0.15) was almost equal to the typical diatom ratio, and the ratio in Type II (0.28) was twice as high as the same ratio. The BSi/POC ratio obtained in the Antarctic Ocean (0.30–0.65) (SMITH and NELSON, 1985; NELSON and SMITH, 1986; NELSON *et al.*, 1989; TRÉGUER *et al.*, 1990) are several times larger than the typical diatom ratio. The high BSi/POC ratio is mostly attributed to Si-rich diatoms which uptake dissolved silica in higher proportion than other elements (TRÉGUER *et al.*, 1990). In the present study, the high BSi/POC ratio also indicates the quantitative importance of diatoms contributing to the total particulate organic matter. Diatom populations in the polar seas may contribute significantly to the global production of biogenic silica of the world ocean as suggested by TRÉGUER and VAN BENNEKOM (1991).

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References

BANAHAN, S. and GOERING, J. J. (1986): The production of biogenic silica and its accumulation on the southeastern Bering Sea shelf. Cont. Shelf Res., **5**, 199–213.

BRZEZINSKI, M. A. (1985): The Si/C/N ratio of marine diatoms: Inter-specific variability and the effect of some environmental variables. J. Phys., **21**, 345–357.

EGGIMAN, D. W. and BETZER, P. R. (1976): Decomposition and analysis of refractory suspended material. Anal. Chem., **48**, 1886–1890.

MCROY, C. P. and GOERING, J. J. (1974): The influence of ice on the primary productivity of the Bering Sea. Oceanography of the Bering Sea with Emphasis on Renewable Resources, ed. by D. W. HOOD and E. J. KELLEY. Fairbanks, Inst. Mar. Sci., Univ. Alaska, 403–421.

MOTODA, S. AND MINODA, T. (1974): Plankton of the Bering Sea. Oceanography of the Bering Sea with Emphasis on Renewable Resources, ed. by D. W. HOOD and E. J. KELLEY. Fairbanks, Inst. Mar. Sci., Univ. Alaska, 207–241.

NELSON, D. M. and SMITH, W. O., Jr. (1986): Phytoplankton bloom dynamics of the western Ross Sea ice-edge-II. Mesoscale cycling of nitrogen and silicon. Deep-Sea Res., **33**, 1389–1412.

NELSON, D. M., SMITH, W. O., Jr., MUENCH, R. D., GORDON, L. I., SULLIVAN, C. W. and HUSBY, D. W. (1989): Particulate matter and nutrient distributions in the ice-edge zone of the Weddell Sea: Relationship to hydrography during late summer. Deep-Sea Res., **36**, 191–209.

OHTANI, K. (1970): Relative transport in the Alaskan Stream in winter. J. Oceanogr. Soc. Jpn., **26**, 271–282.

PAASCHE, E. (1973): Silicon and ecology of marine plankton diatoms. I. *Thalassiosira pseudonana (Cyclotella nana)* growth in a chemostat with silicate as the limiting nutrient. Mar. Biol., **19**, 117–126.

PARSONS, T. R., MAITA, Y. and LALLI, C. M. (1984): A Manual of Chemical and Biological Methods for Seawater Analysis. Oxford, Pergamon Press, 173 p.

REDFIELD, A. C., KETCHUM, B. and RICHARDS, F. A. (1963): The influence of organisms on the composition of seawaters. The Sea, ed. by M. N. HILL. New York, Interscience, 26–77.

SAINO, T. (1979): Primary productivity in the Bering and Chukchi Seas and in the northern North Pacific in 1978 summer. Bull. Plankton Soc. Jpn., **26**, 96–103.

SAMBROTTO, R. N., NIEBAUER, H. J., GOERING, J. J. and LVERSON, R. L. (1986): Relationships among vertical mixing, nitrate uptake, and phytoplankton growth during the spring bloom in the southeast Bering Sea middle shelf. Cont. Shelf Res., **5**, 161–198.

SATO, N., FURUHASHI, K. and EABARA, S. (1981): Extraction method of phytoplankton pigments without grinding for fluorometric measurement employed by Japan Meteorological Agency. Bull. Plankton Soc. Jpn., **28**, 173–178.

SMITH, W. O., Jr. and NELSON, D. M. (1985): Phytoplankton bloom produced by a receding ice edge in the Ross Sea: Spatial coherence with the density field. Science, **227**, 163–166.

TAGUCHI, S. (1972): Mathematical analysis of primary production in the Bering Sea in summer. Biological Oceanography of the Northern North Pacific Ocean, ed. by A. Y. TAKENOUCHI *et al.* Tokyo, Idemitsu Shoten, 253–262.

TANIGUCHI, A. (1969): Regional variations of surface primary production in the Bering Sea in summer and vertical stability of water affecting the production. Bull. Fac. Fish. Hokkaido Univ., **20**, 169–179.

TRÉGUER, P. and VAN BENNEKOM, A. J. (1991): The annual production of biogenic silica in the Antarctic Ocean. Mar. Chem., **35**, 477–487.

TRÉGUER, P., NELSON, D. M., GUENELEY, S., ZEYONS, C., MORVAN, J. and BUMA, A. (1990): The distribution of biogenic and lithogenic silica and the composition of particulate organic matter in the Scotia Sea and the Drake Passage during autumn 1987. Deep-Sea Res., **37**, 833–851.

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