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Chlorophyll-*a* Concentrations in the Bering Sea Basin and the Western and Central Subarctic North Pacific in February 1998: A Comparison between the Bering Sea and the North Pacific

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Chlorophyll-*a* (Chl-*a*) concentrations in the upper 250 m were measured in the Bering Sea basin (between 52°30′N and 58°30′N along 180°; BSB) and the western (between 42°15′N and 51°N along 165°E; WSNP) and central (between 45°N and 49°30′N along 180°; CSNP) subarctic North Pacific in February 1998. Chl-*a* concentrations were found to be near homogenous in the upper mixed layer at every station. Mean±SE within the upper mixed layer was calculated to be $0.34\pm0.01\,\mu g\,l^{-1}$ (range: 0.09–$0.46\,\mu g\,l^{-1}$; $n=45$) in the BSB, $0.57\pm0.01\,\mu g\,l^{-1}$ (0.11–$0.74\,\mu g\,l^{-1}$; $n=52$) in the WSNP and $0.52\pm0.02\,\mu g\,l^{-1}$ (0.14–$0.67\,\mu g\,l^{-1}$; $n=32$) in the CSNP. There were significant differences in the Chl-*a* concentration within the upper mixed layer between the BSB and other two regions. Chl-*a* concentration in the surface waters tended to be lower in the BSB than in the WSNP and CSNP in winter. Chl-*a* concentrations were mostly less than $0.3\,\mu g\,l^{-1}$ below the upper mixed layer in the every region. We suggest that low daily primary production and high respiration and sinking losses are related to the lower Chl-*a* concentration within the upper mixed layer in the BSB.

Key words: Chlorophyll-*a*, Bering Sea, subarctic North Pacific, winter

Introduction

Many shipboard studies have been carried out to determine phytoplankton biomass, chlorophyll-*a* (Chl-*a*), and phytoplankton productivity in the Bering Sea and the subarctic North Pacific in spring and summer (e.g. Kawamura, 1963; Taniguchi, 1969; McRoy *et al.*, 1972; Saino *et al.*, 1979; Welschmeyer *et al.*, 1993; Wong *et al.*, 1995; Shiomoto *et al.*, 1998). Chl-*a* concentrations in the surface waters of the Bering Sea basin (BSB) and the western and central subarctic North Pacific (WSNP and CSNP) are nearly equal (mostly 0.4–$5\,\mu g\,l^{-1}$), and tend to be higher than that (mostly $<0.5\,\mu g\,l^{-1}$) in the eastern subarctic North Pacific (ESNP) (Kawamura, 1963; Odate, 1996; Obayashi *et al.*, 1997). In contrast, very few Chl-*a* concentrations have been measured in winter. The Chl-*a* concentrations in the surface waters were generally 0.3–$0.5\,\mu g\,l^{-1}$ in the BSB (McRoy *et al.*, 1972; Obayashi *et al.*, 1997; Shiomoto *et al.*, 1997, 1999b), 0.5–$1\,\mu g\,l^{-1}$ in the WSNP and CSNP, and about $0.4\,\mu g\,l^{-1}$ in the ESNP (Wong *et al.*, 1995; Obayashi *et al.*, 1997; Shiomoto and Asami, 1999). The previous results show the characteristic that Chl-*a* concentration in the BSB tends to be lower than those in the WSNP and CSNP and seems to be nearly equal to that in the ESNP. However, this characteristic has not yet been confirmed in a single work, and little has been discussed about the factors leading to this characteristic.

A survey on overwintering salmonids in the North Pacific and the Bering Sea was carried out in February 1998 (Anonymous, 1999). Chl-*a* concentration as well as physical and chemical environmental factors were measured in the BSB, WSNP and CSNP during this cruise. In this paper, we show that Chl-*a* concentration tends to be lower in the BSB than in the WSNP and CSNP, and discuss the factors leading to this characteristic.

Materials and Methods

This study was conducted during cruise of the R/V *Kaiyo Maru* (Anonymous, 1999) in the Bering Sea and the western and central North Pacific in February 1998 (Fig. 1). Seawater samples were collected from depths of 0, 10, 20, 30, 50, 75, 100, 125, 150, 200 and 250 m using Niskin samplers attached to a CTD system. Seawater samples ($0.5\,l$) for determining Chl-*a* concentrations were filtered on Whatman GF/F filters. Chl-*a* concentrations were measured on board with a Shimadzu RF-5000 florometer calibrated with commercial Chl-*a* (Sigma Chemical) after extraction with 90% acetone (Parsons *et al.*, 1984). Temperature and salinity were measured with a Sea-Bird 9 plus CTD system. Nitrite+nitrate concentrations were determined with a Bran and Luebbe Auto Analyzer II immediately after collection. Sunlight intensity (visible light, that is, photosynthetically active radiation, PAR) in lux units was recorded at one minute intervals using a photometer installed in the Auto-

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matic Meteorological Monitoring System mounted aboard ship. The lux units were then converted to μmol quanta $m^{-2}s^{-1}$ using the relationship, 1 klux=16.5 μmol quanta $m^{-2}s^{-1}$ (Richardson *et al.*, 1983). The depth of the upper mixed layer was defined as the depth at which the vertical variation of sigma-t reached a maximum at every 1 m.

Results

The subarctic North Pacific is defined as the area north of the Subarctic Boundary, denoted by a vertical 34.0 isohaline in the surface layers (Dodimead *et al.*, 1963). The salinity within the upper mixed layer at Stn. 1, located at the southernmost station in the western North Pacific (Fig. 1), was slightly more than 34.0 (Fig. 3B). The Western Subarctic Gyre is observed in the subarctic North Pacific west of 175°E (e.g. Dodimead *et al.*, 1963). Stations were thus divided into the western subarctic North Pacific (WSNP), which probably included a part of the gyre, the Bering Sea basin (BSB) and the central subarctic North Pacific (CSNP) (Fig. 1).

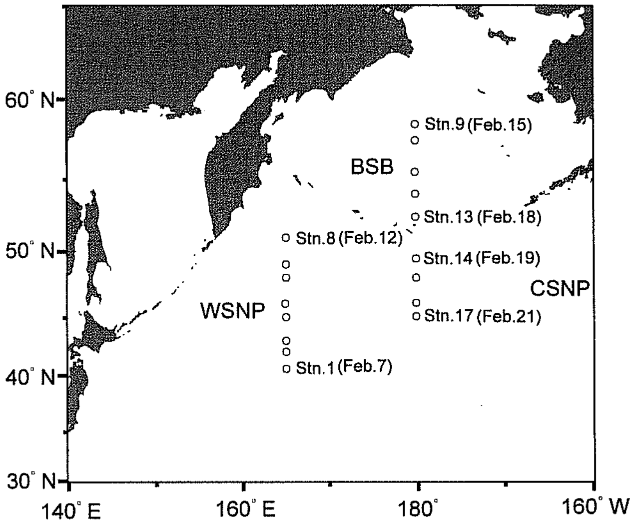

Figure 1. Location of sampling stations in the Bering Sea and the western and central North Pacific in February 1998. WSNP: the western subarctic North Pacific (Stns. 2–8; between 42°15′N and 51°N along 165°E; Feb. 9–12); BSB: the Bering Sea basin (Stns. 9–13; between 52°30′N and 58°30′N along 180°; Feb. 15–18); CSNP: the central subarctic North Pacific (Stns. 14–17; between 45°N and 49°30′N along 180°; Feb. 19–21). Data of sunlight intensity on Feb. 7 and 8 were included in the WSNP.

Sunlight intensity reached a maximum between 10:00 and 14:00 h. The maximum intensity ranged from 196 to 873 μmol quanta $m^{-2}s^{-1}$ in the BSB (Feb. 15–18), from 371 to 1,224 μmol quanta $m^{-2}s^{-1}$ in the WSNP (Feb. 7–12) and from 896 to 1,475 μmol quanta $m^{-2}s^{-1}$ in the CSNP (Feb. 19–21). Total daily sunlight intensity ranged from 3.0 to 11.9 mol quanta $m^{-2}d^{-1}$ in the BSB, from 7.1 to 14.7 mol quanta $m^{-2}d^{-1}$ in the WSNP and from 9.8 to

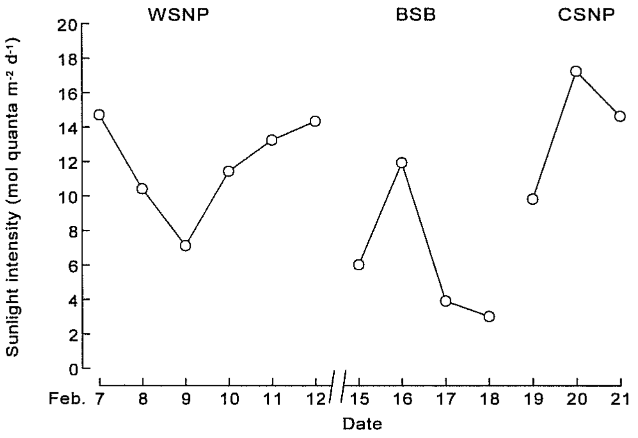

Figure 2. Total daily sunlight intensity (mol quanta $m^{-2}d^{-1}$) in the western subarctic North Pacific (WSNP), the Bering Sea basin (BSB) and the central subarctic North Pacific (CSNP).

Table 1. Mean±standard error (SE) of total daily sunlight intensity, mixed layer depth, sigma-t gradient in the pycnocline, temperature and salinity at 50 m, nitrite+nitrate and chlorophyll-*a* concentrations within the upper mixed layer and chlorophyll-*a* standing stock integrated in the upper 250 m in the Bering Sea basin (BSB), the western subarctic North Pacific (WSNP) and the central subarctic North Pacific (CSNP). The figures in parentheses indicate the number of data for calculating mean±SE.

	BSB		WSNP		CSNP	
Daily sunligth intensity (mol quanta $m^{-2}d^{-1}$)	6.2±2.0	(4)	11.9±1.2	(6)	13.9±2.2	(3)
Mixed layer depth (m)	174±11	(5)	130±8	(7)	143±17	(4)
Sigma-t gradient ($\times 10^{-2}$ kg m^{-4})	3.21±1.26	(4)	7.73±1.48	(7)	6.29±1.29	(4)
Temperature (°C)	2.3±0.3	(5)	3.5±0.4	(7)	4.7±0.8	(4)
Salinity	33.037±0.047	(5)	33.071±0.055	(7)	33.082±0.123	(4)
NO_2+NO_3 (μM)	26.4±0.4	(45)	18.4±0.4	(52)	17.7±0.8	(32)
Chl-*a* (μg l^{-1})	0.34±0.01	(45)	0.57±0.01	(52)	0.52±0.02	(32)
Chl-*a* standing stock (mg m^{-2})	62.2±2.3	(5)	81.2±7.3	(7)	79.2±5.8	(4)

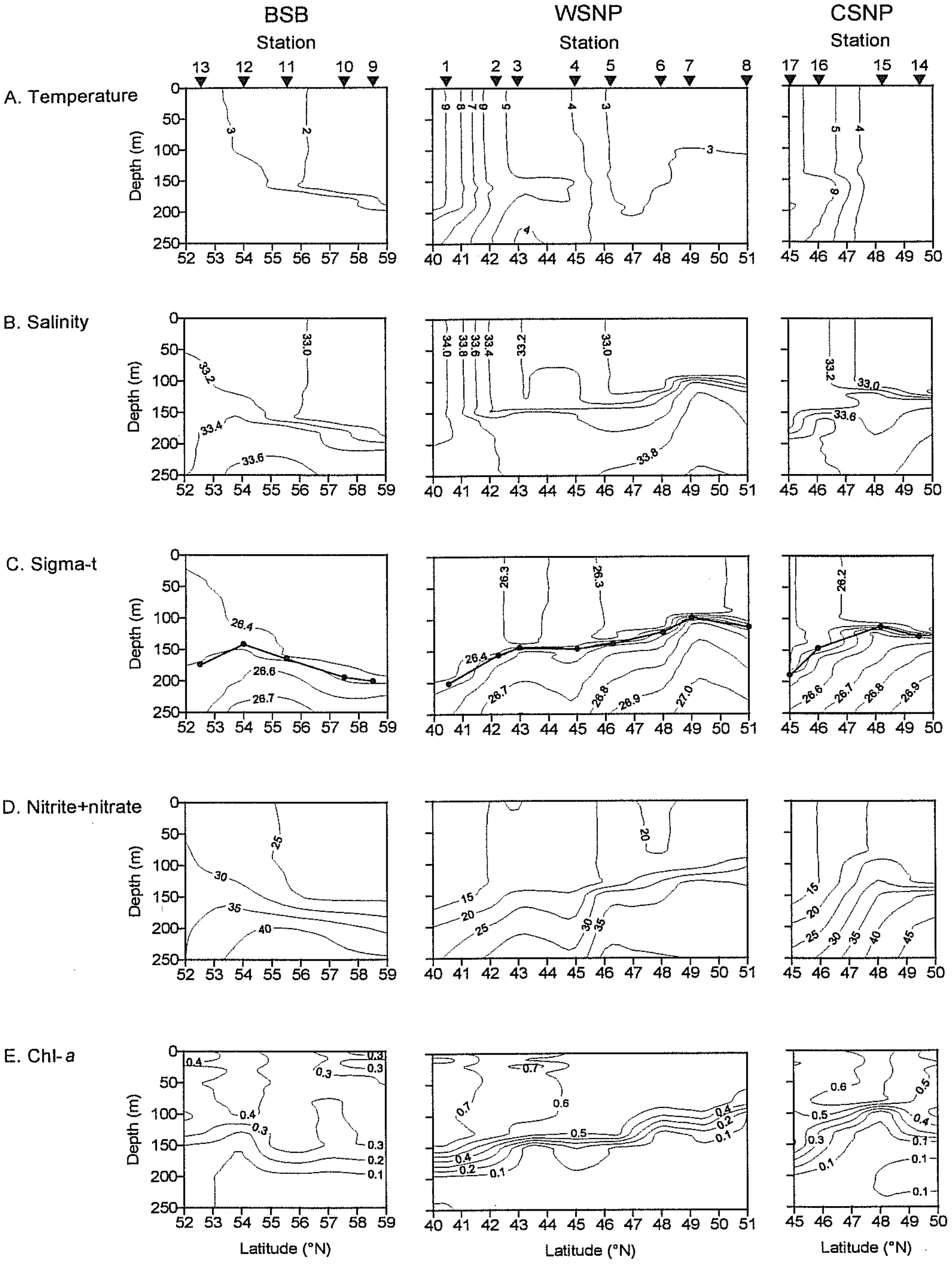

Figure 3. Vertical sections in temperature (°C; A), salinity (B) and sigma-t (C), nitrite+nitrate concentrations (μM; D) and chlorophyll-*a* concentrations ($\mu g\, l^{-1}$; E) in the Bering Sea basin (BSB), the western subarctic North Pacific (WSNP) and the central subarctic North Pacific (CSNP) in February 1998. In Fig. 3C, solid circles indicate the depth of the upper mixed layer.

17.2 mol quanta $m^{-2} d^{-1}$ in the CSNP (Fig. 2). The mean value in the BSB was about half of those in the WSNP and CSNP (Table 1), though there were no significant differences in the total daily sunlight intensity between the BSB and WSNP and between the BSB and CSNP (Mann-Whitney *U*-test, $p>0.05$, two-tailed test). The total daily sunlight intensity tended to be lower in the BSB than in the other two regions.

The depths of the upper mixed layer ranged from 141 to 200 m in the BSB, from 97 to 156 m in the WSNP and from 111 to 188 m in the CSNP (Fig. 3C). The mean of the depths in the BSB was deeper than those in the WSNP and

CSNP (Table 1). The sigma-t gradients at the bottom of the upper mixed layer in the BSB seemed to be gentler than those in the WSNP and CSNP (Fig. 3C). The gradient was significantly different between the BSB and WSNP (*U*-test, $p<0.05$), but not between the BSB and CSNP (*U*-test, $p>0.05$). The mean value of the gradient in the BSB was about half of those in the WSNP and CSNP (Table 1). The depth of the upper mixed layer tended to be deeper in the BSB than in the other two regions, and the gradient of pycnocline tended to be lower in the BSB than in the others.

The temperature within the upper mixed layer was 1–4°C in the BSB, 2–6°C in the WSNP and 3–7°C in the CSNP (Fig. 3A). Temperature at 50 m, which represents the temperature within the upper mixed layer, was significantly different between the BSB and CSNP (*U*-test, $p<0.05$), but not between the BSB and WSNP (*U*-test, $p>0.05$). Mean of temperatures at 50 m depth in the BSB was about 1.5 times as low as that in the WSNP and about twice as low as that in the CSNP (Table 1). The temperature within the upper mixed layer tended to be lower in the BSB than in the other two regions. The salinity within the upper mixed layer was 32.9–33.3 in the BSB, 32.9–33.8 in the WSNP and 32.8–33.5 in the CSNP (Fig. 3B). The mean of salinity at 50 m depth was nearly equal in the three regions (Table 1). The tempearture and salinity below the upper mixed layer were less than 7°C and more than 33.0 in every region.

Nitrite+nitrate concentrations were nearly uniform within the upper mixed layer and increased with depth below the layer (Fig. 3D). The concentrations within the upper mixed layer were generally 20–35 μM in the BSB, and 10–30 μM in the WSNP and CSNP. There were significant differences in the nutrient concentrations between the BSB and WSNP, and between the BSB and CSNP (*U*-test, $p<0.0001$). The mean of the nutrient concentrations in the BSB was about 1.5 times as high as those in the WSNP and CSNP (Table 1). The nitrite+nitrate concentrations within the upper mixed layer tended to be higher in the BSB than in the other two regions.

Chl-*a* concentrations were nearly uniform within the upper mixed layer and decreased with depth below the layer (Fig. 3E). Chl-*a* concentrations within the upper mixed layer were 0.09–0.46 $\mu g\, l^{-1}$ in the BSB, 0.11–0.74 $\mu g\, l^{-1}$ in the WSNP and 0.14–0.67 $\mu g\, l^{-1}$ in the CSNP. There were significant differences in the Chl-*a* concentrations between the BSB and WSNP, and between the BSB and CSNP (*U*-test, $p<0.0001$). The mean of the Chl-*a* concentration in the BSB was roughly half of those in the WSNP and CSNP (Table 1). The Chl-*a* concentration within the upper mixed layer tended to be lower in the BSB than in the other two regions. On the other hand, the Chl-*a* concentrations were mostly less than 0.3 $\mu g\, l^{-1}$ below the upper mixed layer in every region.

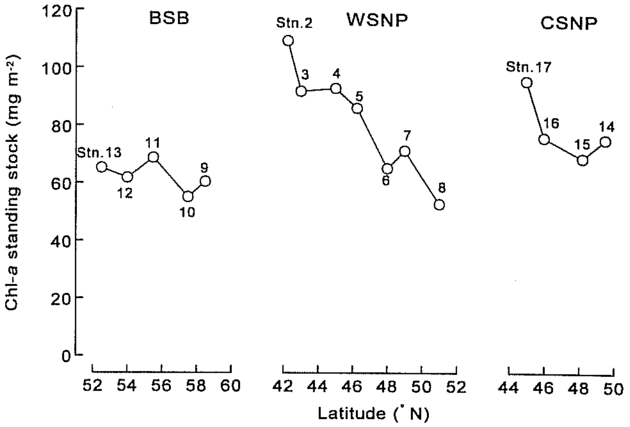

Figure 4. Variations in chlorophyll-*a* standing stock integrated in the upper 250 m (mg m^{-2}) in the Bering Sea basin (BSB), the western subarctic North Pacific (WSNP) and the central subarctic North Pacific (CSNP) in February 1998.

Chl-*a* standing stock was estimated by integrating the Chl-*a* concentrations in the upper 250 m. The Chl-*a* standing stock ranged from 55.0 to 68.6 mg m^{-2} in the BSB, from 52.7 to 109.3 mg m^{-2} in the WSNP and from 69.0 to 95.9 mg m^{-2} in the CSNP (Fig. 4). Most of the Chl-*a* standing stocks in the BSB were lower than those in the WSNP, though there was no significant difference between the BSB and the WSNP (*U*-test, $p>0.05$). Mean of the Chl-*a* standing stocks in the BSB was about 80% of those in the WSNP and CSNP (Table 1). The Chl-*a* standing stock tended to be lower in the BSB than in the other two regions, a pattern which is similar to that in Chl-*a* concentration within the upper mixed layer.

Discussion

Mean Chl-*a* concentration in the upper mixed layer was 0.34 $\mu g\, l^{-1}$ in the BSB, 0.57 $\mu g\, l^{-1}$ in the WSNP and 0.52 $\mu g\, l^{-1}$ in the CSNP (Table 1). Chl-*a* concentrations in the surface waters reported by previous studies in winter were 0.3–0.5 $\mu g\, l^{-1}$ in the BSB (McRoy *et al.*, 1972; Obayashi *et al.*, 1997; Shiomoto *et al.*, 1997, 1999b) and 0.5–1 $\mu g\, l^{-1}$ in the WSNP and CSNP (Obayashi *et al.*, 1997; Shiomoto and Asami, 1999). The Chl-*a* concentrations in the three regions in this study were nearly equal to those in the corresponding regions in the previous studies, though our results were generally identified to be in the lower part of the past results. Moreover, the wintertime feature of Chl-*a* concentrations within the upper mixed layer indicated by combining some previous studies (McRoy *et al.*, 1972; Obayashi *et al.*, 1997; Shiomoto *et al.*, 1997, 1999b; Shiomoto and Asami, 1999), that is, the lower Chl-*a* concentration in the BSB compared with the WSNP and CSNP, was confirmed in our work.

Primary productivity per hour unit at the surface obtained around noon was reported to be between 0.3 and 0.5 μgC l^{-1} h^{-1} in the BSB during January to March 1993 (Shiomoto *et al.*, 1999b) and between 0.2 and 0.6 μgC l^{-1} h^{-1} in the WSNP and CSNP in February 1996 (Shiomoto and Asami, 1999). In winter, sunlight intensity is substantially lower in the Bering Sea than in the subarctic North Pacific and the daytime hours are shorter in the Bering Sea than in the subarctic North Pacific, indicating that total daily sunlight intensity is lower in the Bering Sea than in the subarctic North Pacific. This general feature was also observed in this study (Fig. 2; Table 1). Consequently, daily primary production (e.g. unit: mgC m^{-2} d^{-1}) depending on primary productivity per hour unit and total daily sunlight intensity was possibly lower in the BSB than in the WSNP and CSNP.

The depth of the upper mixed layer tended to be deeper in the BSB than in the WSNP and CSNP (Fig. 3C; Table 1). This trend is considered to be a general feature in winter (Ohtani, 1973; Obata *et al.*, 1996). According to Sverdrup (1953), global monthly critical depth was estimated to be 0–50 m in the BSB and 0–100 m in the WSNP and CSNP in winter, especially 50–100 m in the subarctic North Pacific in February (Obata *et al.*, 1996). It is thus implied that upper mixed layer to the critical depth tends to be deeper in the BSB compared with the WSNP and CSNP. This suggests that respiration loss throughout the water column for the phytoplankton community tends to be greater in the BSB than in the WSNP and CSNP in winter, especially in February.

Semina and Tarkhova (1972) showed that the amount of phytoplankton standing stock was proportional to the strength of the density gradient in the main pycnocline. This is probably because a steep gradient favors the retention of phytoplankton cells by halting their sinking below the upper mixed layer. The gradient of the pycnocline tended to be lower in the BSB than in the WSNP and CSNP (Fig. 3C; Table 1). Hence, the level of phytoplankton cell loss by sinking below the upper mixed layer seemed to be higher in the BSB than in the other two regions.

Copepod grazing generally has an effect on large phytoplankton (more than 8 μm cell size; Landry *et al.*, 1993); variation in the large phytoplankton contributes to that of the total Chl-*a* concentration (Malone, 1980; Raimbault *et al.*, 1988; Odate and Maita, 1988/1989; Odate, 1996). Accordingly, copepod grazing influences the total Chl-*a* concentration. Subarctic oceanic species such as *Neocalanus plumchrus*, *N. cristatus*, *Eucalanus bungii* and *Metridia pacific* are predominantly distributed in the central and western Bering Sea and the subarctic North Pacific in summer (Motoda and Minoda, 1974; Miller *et al.*, 1984; Coyle *et al.*, 1996). Few of these copepods occur in the surface layers in winter (Fulton, 1973; Miller *et al.*, 1984; Coyle *et al.*, 1996). In the subarctic North Pacific, the wet weight of copepods, obtained with the vertical tow of a Norpac net (mesh size: 335 μm) from 150 m to the surface, shows a tendency to be considerably lower in winter ($<$30 mg m^{-3}) than in summer ($<$500 mg m^{-3}) (Shiomoto *et al.*, 1998, 1999a; Shiomoto and Asami, 1999). The identical trend is found for macrozooplankton (principally copepods) biomass in the upper 200 m in the oceanic regions of the Bering Sea (mesh size of net: 168, 330 or 350 μm; wet weights were generally $<$50 mg m^{-3} in winter and $<$750 mg m^{-3} in summer) (Motoda and Minoda, 1974; Coyle *et al.*, 1996). Copepods probably have much less grazing impact on phytoplankton in winter compared to that in summer, in the subarctic regions. The wet weight of copepods was measured simultaneously on this cruise with the vertical tow of a Norpac net from 150 m to the surface (Nagasawa *et al.*, 1999). The wet weight was from 1.7 to 5.4 mg m^{-3} (mean±SE: 3.6±0.7 mg m^{-3}, $n=5$) in the BSB, from 3.4 to 39.3 mg m^{-3} (14.2±4.5 mg m^{-3}, $n=7$) in the WSNP and from 5.9 to 17.4 mg m^{-3} (11.7±2.5 mg m^{-3}, $n=4$) in the CSNP. The values are nearly equal to those previously reported in the wintertime studies, implying a very low grazing effect on phytoplankton. Moreover, the wet weight in the BSB was significantly different from those in the WSNP and CSNP (*U*-test, $p<0.05$). The mean value in the BSB was about four times as low as those in the other two regions. The ambient surface temperature is lower in the Bering Sea than in the subarctic North Pacific in winter (Table 1; Ohtani, 1970; Anonymous, 1993), indicating that zooplankton grazing is possibly less active in the BSB. Consequently, copepod grazing impact on phytoplankton was rather lower in the BSB than in the WSNP and CSNP.

We therefore suggest that daily primary production is lower, respiration loss is higher and sinking loss is greater in the BSB than in the WSNP and CSNP, and hence these factors cause the lower Chl-*a* concentration in the wintertime BSB.

We did not measure Chl-*a* concentrations in the ESNP on this cruise. Many observations for measuring Chl-*a* concentrations have been carried out in the ESNP even in winter and the concentrations are about 0.4 μg l^{-1} (e.g. Wong *et al.*, 1995; Obayashi *et al.*, 1997; Shiomoto and Asami, 1999). The previous results in the ESNP and our results in the BSB, WSNP and CSNP show that Chl-*a* concentrations in the surface waters were nearly equal in the BSB and ESNP, and in the WSNP and CSNP, and that the concentrations were lower in the former regions than in the latter regions. Shiomoto and Asami (1999) suggested that iron and microzooplankton grazing may be related to the lower Chl-*a* concentration in the region east of 180° compared to that in the region west of 180°. The factors leading to the similar low Chl-*a* concentration seem to be different between the BSB and ESNP.

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1998年2月におけるベーリング海盆域と西部ならびに中部北太平洋亜寒帯域のクロロフィル*a*濃度：ベーリング海と北太平洋との比較

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250m以浅のクロロフィル*a*濃度を1998年2月のベーリング海盆域（52°30′–58°30′N，180°）と西部（42°15′–51°N，165°E）ならびに中部（45°–49°30′N，180°）北太平洋亜寒帯域において測定した．表層混合層内のクロロフィル*a*濃度はほぼ均一であり，その平均値±標準誤差を求めるとベーリング海盆域で0.34±0.01 $\mu g\,l^{-1}$（範囲：0.09–0.46 $\mu g\,l^{-1}$；n=45），西部北太平洋亜寒帯域で0.57±0.01 $\mu g\,l^{-1}$（0.11–0.74 $\mu g\,l^{-1}$；n=52），中部北太平洋亜寒帯域で0.52±0.02 $\mu g\,l^{-1}$（0.14–0.67 $\mu g\,l^{-1}$；n=32）であった．表層混合層内のクロロフィル*a*濃度にはベーリング海盆域と北太平洋亜寒帯域との間に統計的に有意な差が認められた．したがって，ベーリング海盆域における表層混合層内のクロロフィル*a*濃度は西部や中部の北太平洋亜寒帯域に比べて低い傾向にあることが分かった．一方，表層混合層以深ではいずれの水域でも大半の値は0.3 $\mu g\,l^{-1}$以下であった．低い日生産量，高い呼吸や沈降によるロスがベーリング海盆域における低いクロロフィル*a*濃度に関わっていることが示唆された．

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