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East-west distributions of chlorophyll *a*, primary productivity and their size compositions in the early winter subarctic North Pacific

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Abstract : East-west distributions of total and size-fractionated (10–200, 2–10 and <2 μm) chlorophyll *a* concentration and primary productivity were determined at the surface in the subarctic North Pacific during November and December 1992. Higher total chlorophyll a concentrations exceeding about 1 μg l^{-1} were observed at stations west of 165° W, the western and central subarctic North Pacific (W&CSNP), compared to those of the eastern subarctic North Pacific (ESNP), located east of 165° W. Total primary productivity followed identical regional trend at the stations with values exceeding 1.5 μg C l^{-1} h^{-1}. Large phytoplankton, the 10–200 μm fraction, generally contributed to the high total chlorophyll *a* concentrations and primary productivity. Out of several environmental factors considered under the present study, wind velocity tended to be higher at stations in the W&CSNP than at those in the ESNP. High wind velocity induces more turbulent water column conditions, and such conditions favor large cells. We thus suggest that more turbulent water conditions induced by high wind velocity was an advantageous factor for survival of large phytoplankton in the surface layer, and hence the high total chlorophyll *a* concentration and primary productivity were achieved in the W&CSNP.

Keywords : *Chlorophyll a, Primary productivity, Size composition, Winter North Pacific*

1. Introduction

In the subarctic North Pacific in summer, chlorophyll *a* concentration in the surface layer tends to be higher in the western region (mostly 0.5–1 μg l^{-1}) than in the eastern region (mostly <0.5 μg l^{-1}) (KAWAMURA, 1963 ; ODATE, 1996 ; OBAYASHI *et al.*, 1997 ; SHIOMOTO *et al.*, 1998). However, primary productivity does not always show the same trend ; for example, daily primary productivity was not substantially different between in the western region (278–1,397mg C m^{-2} d^{-1}) and in the eastern region (290–1,550 mg C m^{-2} d^{-1}) (SHIOMOTO *et al.*, 1998). Small phytoplankton of less than 5 μm dominate the phytoplankton community in the subarctic North Pacific during spring and summer, accounting for 40–80% of the total chlorophyll *a* concentration, except phytoplankton bloom when large phytoplankton of more than 10 μm account for more than about 80% of the total chlorophyll *a* concentration (BOOTH, 1988 ; ODATE and MAITA, 1988/89 ; ODATE, 1994, 1996 ; SHIOMOTO *et al.*, 1997). Likewise, the small phytoplankton contribute significantly to the primary productivity of the phytoplankton community, generally accounting for 50–70% (WELSCHMEYER *et al.*, 1993 ; SHIOMOTO *et al.*, 1997).

In contrast, only a little is known about the east–west distributions of the chlorophyll *a*

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concentration, primary productivity and their size compositions in winter. OBAYASHI *et al.* (1997) showed no substantial difference in chlorophyll *a* concentration (mostly $<0.4\ \mu g\ l^{-1}$) between the eastern and western regions. SHIOMOTO and ASAMI (1999) reported the high west and low-east distribution patterns of chlorophyll *a* concentration (mean at the surface was $0.62\ \mu g\ l^{-1}$ in the west and $0.44\ \mu g\ l^{-1}$ in the east) and primary productivity (mean at the surface was $0.45\ \mu g\ C\ l^{-1}\ h^{-1}$ in the west and $0.29\ \mu g\ C\ l^{-1}\ h^{-1}$ in the east). A few studies in winter indicated the identical trends as those in spring and summer in the contribution of the small phytoplankton to chlorophyll *a* concentration and primary productivity (BOYD *et al.*, 1995a, b ; SHIOMOTO *et al.*, 1997). Hence, there is a necessity to acquire information about the east-west distributions of them in the wintertime subarctic North Pacific.

In this paper, we report the east-west distributions of the size-fractionated chlorophyll *a* concentration and primary productivity at the surface in November-December 1992, and discuss the factors leading to their distributions.

2. Materials and Methods

Water sampling and incubation experiments were conducted during the cruise of the R/V *Kaiyo Maru* belonging to the Fisheries Agency of Japan in the northern North Pacific during November and December 1992 (Fig. 1). Surface seawater samples were collected around noon using an acid-cleaned plastic bucket and were then sieved through a $200\ \mu m$ mesh screen to remove large zooplankton.

Total and size-fractionated chlorophyll *a* concentrations were measured by fluorometry (PARSONS *et al.* 1984). Total chlorophyll *a* was determined in samples filtered through 47mm Whatman GF/F filters. Size-fractionated chlorophyll *a* was measured in samples obtained as follows : seawater samples were filtered through 2 and $10\ \mu m$ pore size Nuclepore filters and the filtrates were then refiltered onto 47 mm Whatman GF/F filters(<2 and $<10\ \mu m$ fractions). The filters were then stored frozen at -20℃ until analysis ashore.Pigments were extracted in 90% acetone and the fluorescence was measured with a Hitachi F−2000 fluorophotometer. Calibration of the fluorophotometer was performed with commercially prepared chlorophyll *a* from Wako Pure Chemical Industries, Ltd. (Tokyo). Chlorophyll *a* concentrations for the 2–10 and $10–200\ \mu m$ fractions were obtained from the differences between the <10 and $<2\ \mu m$ fractions and between the total and $<10\ \mu m$ fraction, respectively.

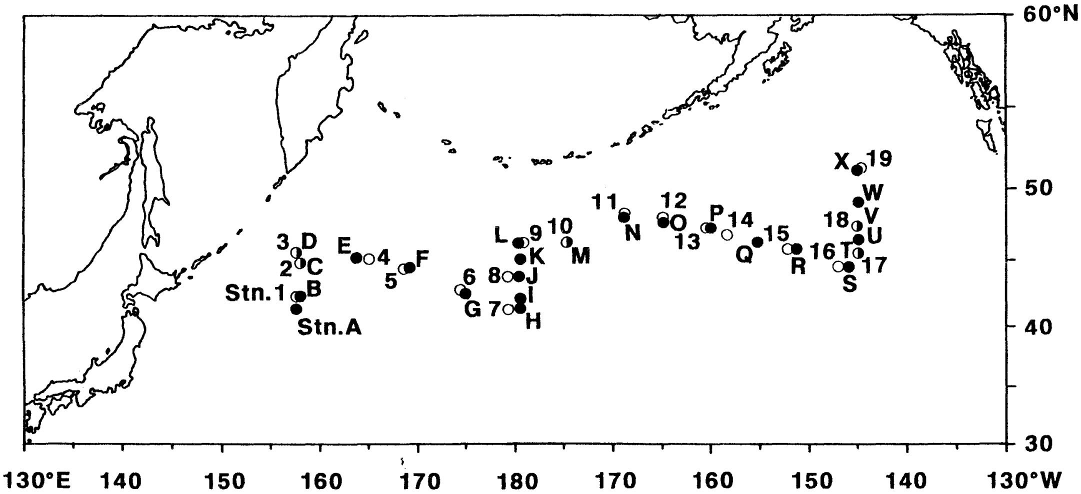

Fig. 1. Location of sampling stations in the subarctic North Pacific between November 28 and December 18, 1992. ○ : stations for measuring chlorophyll *a* concentration and primary productivity at the surface ; ● : stations for the CTD casts. As station, numeral and alphabet are attached to open and solid circles, respectively.

Total and size-fractionated primary productivity was determined by the ^{13}C method (HAMA *et al.*, 1983). The primary productivity experiments were started within 1 hour after sampling. The seawater samples (1-l) were dispensed into six acid-cleaned 1-l polycarbonate bottles and enriched by the addition (1-ml) of $NaH^{13}CO_3$ (99 atom% ^{13}C ; Shoko Co., Ltd., Tokyo) to about 10% of the total inorganic carbon in ambient water. Incubations were conducted under sunlight and were cooled with near-surface seawater for 2-3 hours. The fractionation of the samples into size classes was carried out after incubation. Immediately following incubation, two samples were filtered directly through precombusted (450℃ for 4 hours) 47mm Whatman GF/F filters (total). Two of the remaining four samples were filtered through a Neclepore filter with a pore size of 2 μm and another two with a pore size of 10 μm. The filtrate was refiltered onto 47mm Whatman GF/F filters(<2 and <10 μm fractions) and the particulate matter on the Whatman GF/F filters was rinsed with prefiltered seawater. The filters were then stored frozen at −20℃ until analysis ashore. They were treated with HCl fumes for 4 hours to remove inorganic carbon and completely dried in a vacuum desiccator. The isotopic ratios of ^{13}C to ^{12}C and particulate organic carbon were determined through infrared absorption spectrometry using a JACSO EX-130S $^{13}CO_2$ analyzer (Japan Spectroscopic Co., Ltd., Tokyo ; c.f., SATOH *et al.*, 1985). Total inorganic carbon in the water was measured with an infrared analyzer (Shimadzu TOC 5000). Primary productivity was calculated according to the equation described by HAMA *et al.* (1983). Size fractionated primary productivity was estimated in the same manner as the chlorophyll a concentration. Repeatability of the experiment was 7.3% as the coefficient of variation for nine replications.

The surface temperature and salinity were measured with a thermometer and an Auto Lab salinometer. Surface nutrient concentrations were immediately determined using a Bran and Luebbe Auto Analyzer II. Atmospheric pressure, wind speed and incident solar radiation were recored at ten-minute intervals by an Automatic Meteorological Observation System (SCS-9810ED ; Nippon Electric Instrument Inc., Tokyo) mounted aboard ship. In addition, vertical profiles of temperature and salinity down to 1000 m were measured at stations whose locations were different from the locations of stations for measuring phytoplankton chlorophyll *a* and primary productivity, using a Neil Brown CTD Mark II or a Sea Bird memory CTD.

Vertical tows with a Norpac net (mesh size : 335 μm) equipped with a calibrated flowmeter were conducted from a depth of 150m to the surface nearby the stations for CTD casts irrespective of day or night (NAGASAWA *et al.*, 1997). The contents were fixed in a 10% neutralized formaline seawater solution. Zooplankton were sorted into the following categories in the laboratory : euphausiids, copepods, pteropods, appendicularians, chaetognaths, ostracods, jellyfishes, salps, fishes, squid and others. Wet weight was measured for each category.

3. Results

The crest and trough of atmopheric pressure were observed for a period of about 3 or 4 days (Fig. 2a). High wind velocities were observed during or after the passage of low atmospheric pressure(Fig. 2b). In particluar, wind velocities exceeding 15 m s^{-1} were observed between November 28 and December 13, that is, to the west of 160° W, but such high wind velocities were not found after December 13, that is, to the east of 160° W (Gulf of Alaska). Daily solar radiation ranged from 1.8 to 12.4 mol quanta m^{-2} d^{-1} (Fig. 2c).

The subarctic North Pacific is defined as the area north of the Subarctic Boundary, denoted as a vertical 34.0 isohaline in the surface layers (DODIMEAD *et al.*, 1963). Based on the surface salinity data, we judged whether or not a station was located in the subarctic North Pacific (surface salinity <34.0).

Water temperature and salinity at the surface were respectively within the range of 4.5–10.6℃ and 32.774–33.849 at the stations along the sampling tract (Fig. 3a, b). Nitrite + nitrate concentrations were in the range of 3.3 and 20.1 μM (Fig. 3c). The depths of the upper mixed layer, defined as the depth where the vertical

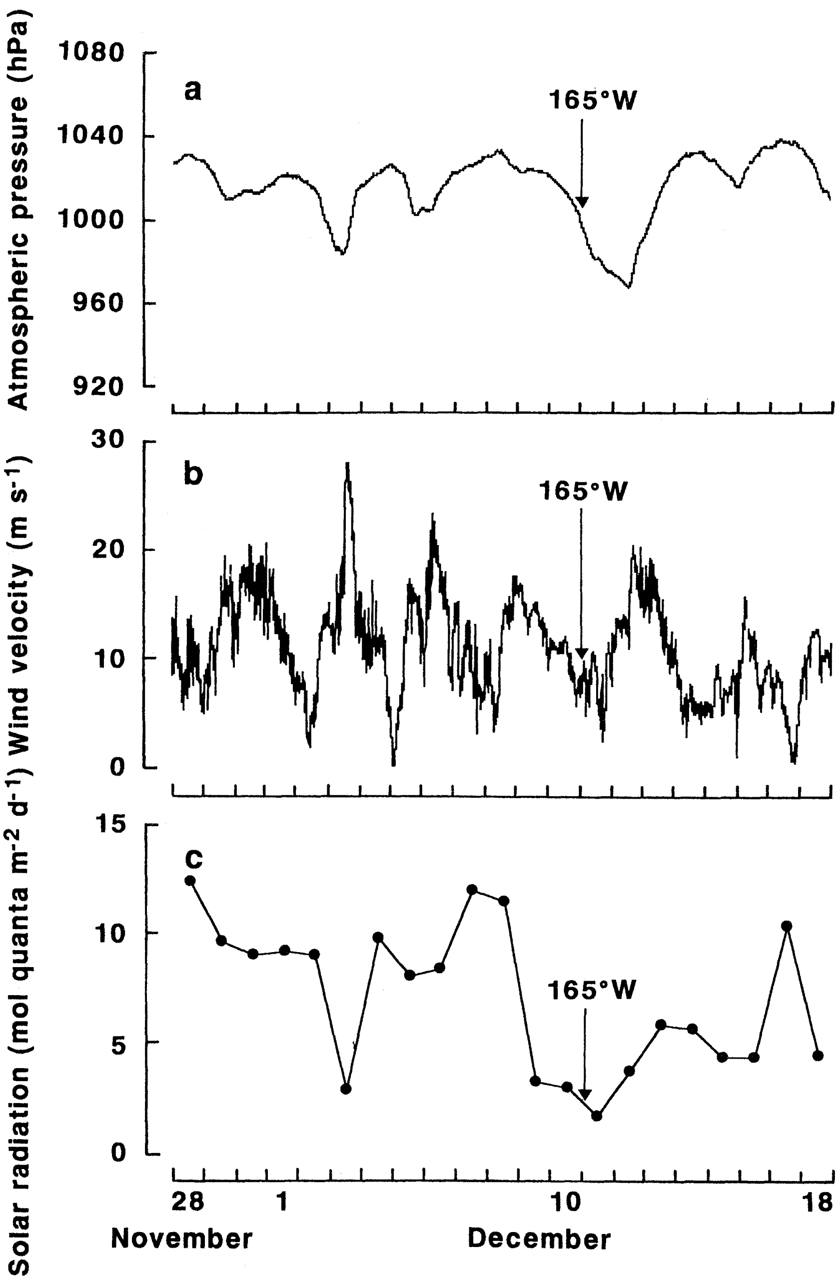

Fig. 2. Variations in atmospheric pressure (a), wind velocity (b) and daily solar radiation calculated by integrating the data recorded at ten-minute intervals (c). Solar radiation was monitored in lux units and the lux units were converted to μmol quanta m^{-2} s^{-1} using the relationship, 1 Klux = 16.5 μmol quanta m^{-2} s^{-1} (RICHARDSON *et al.*, 1983).

variation of sigma-t became maximum, ranged from 57 to 152 m (Fig. 3d).

Total chlorophyll *a* concentrations ranged from 0.20 to 2.41 μg l^{-1} and showed 12-fold variations (Fig.4a). High chlorophyll *a* concentrations exceeding 1 μg l^{-1} were observed at

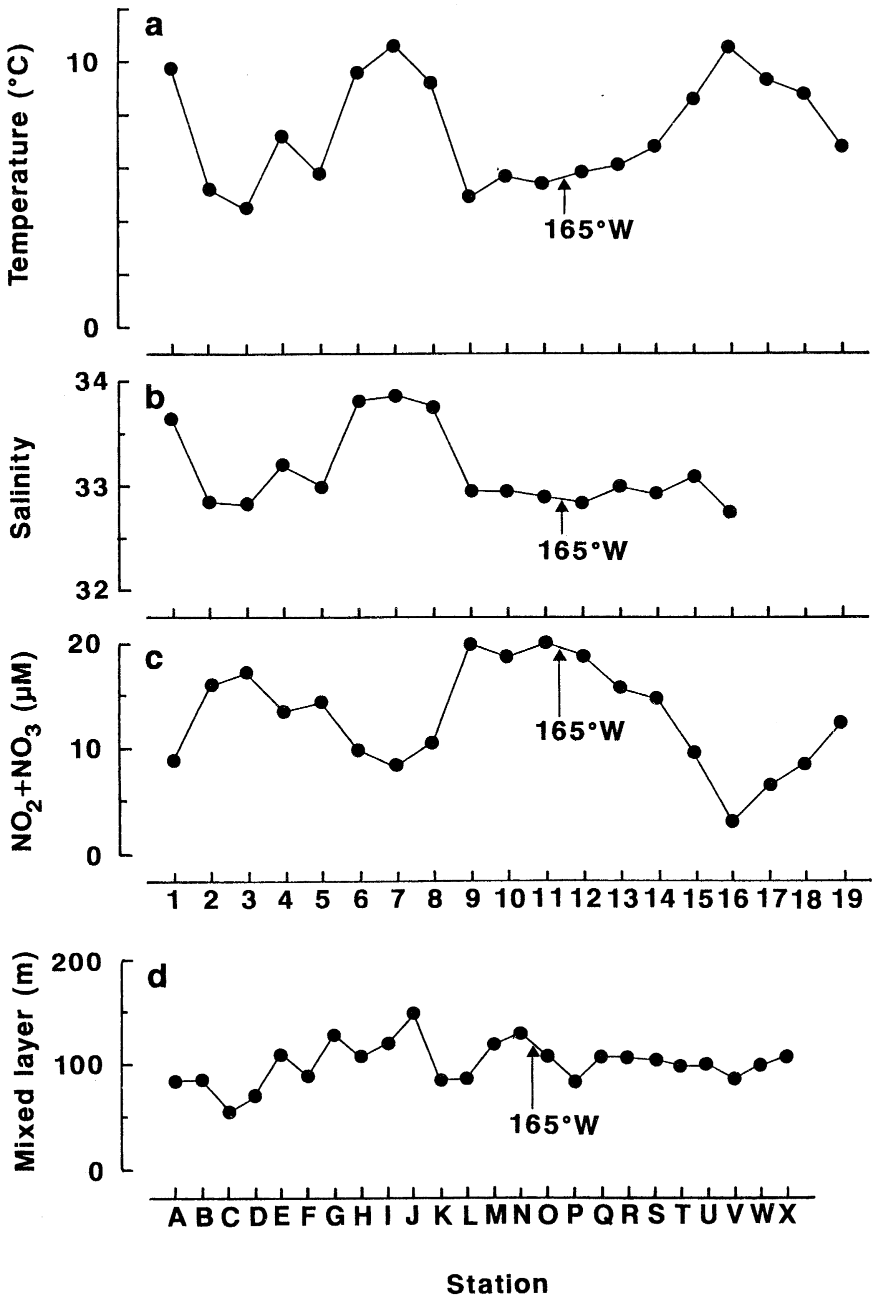

Fig. 3 Variations in temperature (a), salinity (b) and nitrite + nitrate concentration (c) at the surface, and depth of the upper mixed layer (d).

Stns. 1, 2, 6, 9 and 11 ; and a high value nearly equal to 1 $\mu g\ l^{-1}$ was found at Stn. 7. These stations were located in the region west of 165° W (Fig.1). The values at the remaining stations were within the range of 0.20 and 0.74 $\mu g\ l^{-1}$. These values showed 3.7-fold variations and were rather uniform. The percentage contributions of the 10–200 μm fraction to total chlorophyll *a* concentration were highest at Stns. 1, 6, 7, 9 and 11 with high total chlorophyll *a*

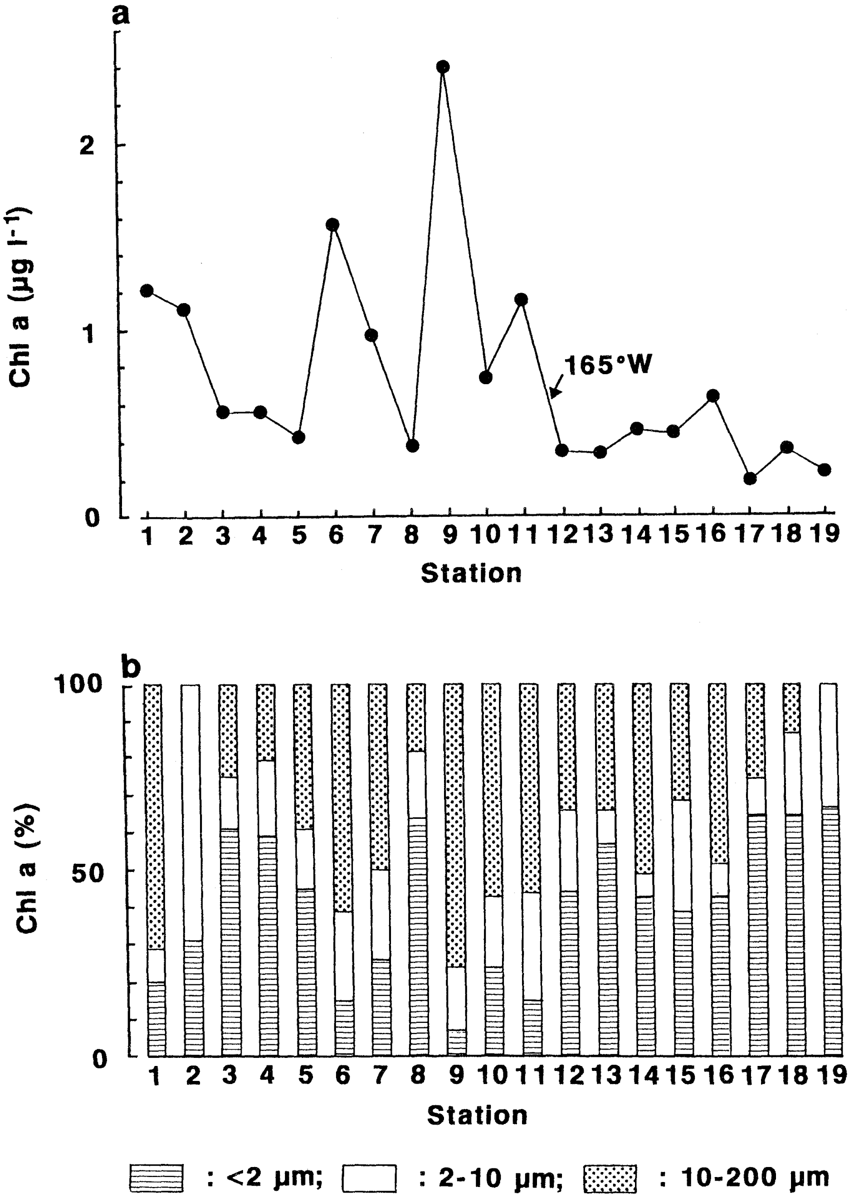

Fig. 4 Variations in total chlorophyll *a* concentration (a) and percentage composition of chlorophyll *a* concentration (b) at the surface.

concentrations (> about 1 μg l^{-1}), and at Stns. 10, 14 and 16 with relatively low total chlorophyll *a* concentration, accounting for 48–76% of total chlorophyll *a* (Fig. 4b). The <2 μm fraction dominated total chlorophyll a concentrations at the remaining stations, with the exception of Stn. 2 where the percentage contribution of the 2–10 μm fraction was highest.

Total primary productivity ranged from 0.45 to 3.17 μg C l^{-1} h^{-1} and showed 7-fold variations (Fig. 5a). High primary productivity exceeding 1.5 μg C l^{-1} h^{-1} was observed at Stns. 2, 6, 7, 9 and 16. These stations except one (Stn. 16) were located in the region west of 165° W (Fig. 1). Excluding these high values, the remaining values were within the range of

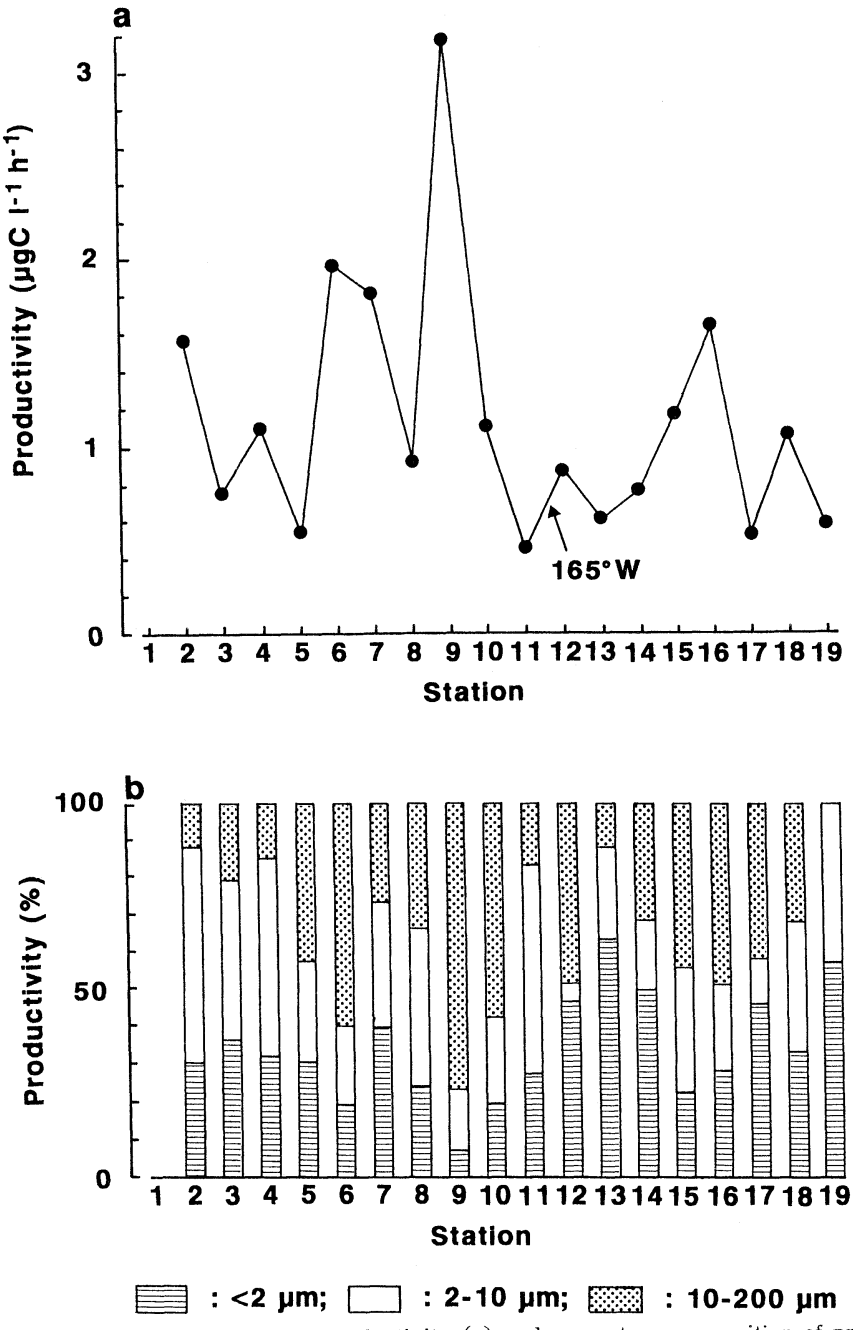

Fig. 5 Variations in total primary productivity (a) and percentage composition of primary productivity (b) at the surface.

0.45 and 1.17 μg C l^{-1} h^{-1} and showed 2.6-fold variations marked with rather an uniform trend. The percentage contributions of the 10–200 μm fraction to total primary productivity were highest at Stns. 6, 9 and 16 with high total primary productivity (>1.5 μg C l^{-1} h^{-1}), and at Stns. 5, 10, 12 and 15 with relatively low total primary productivity, accounting for 43–77% of

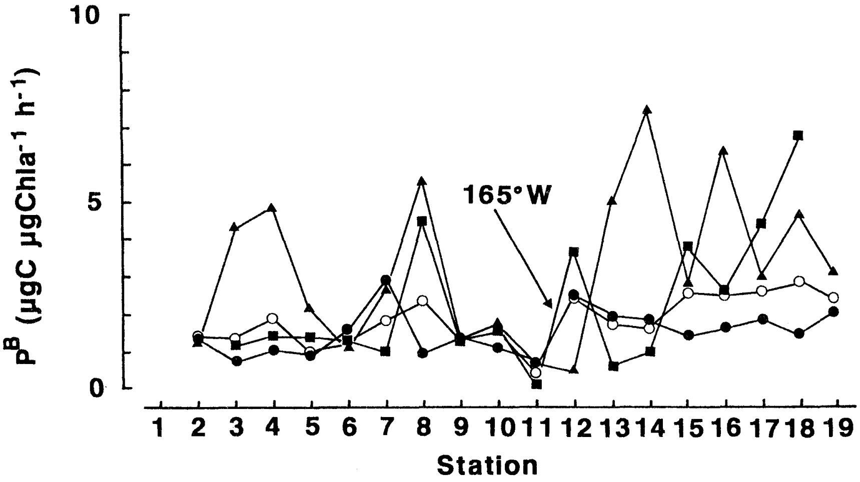

Fig. 6 Variations in total and size-fractionated chlorophyll *a*-specific primary productivity (P^B) at the surface. ○ : total ; ● : <2 μm fraction ; : 2–10 μm fraction ; ■ : 10–200 μm fraction.

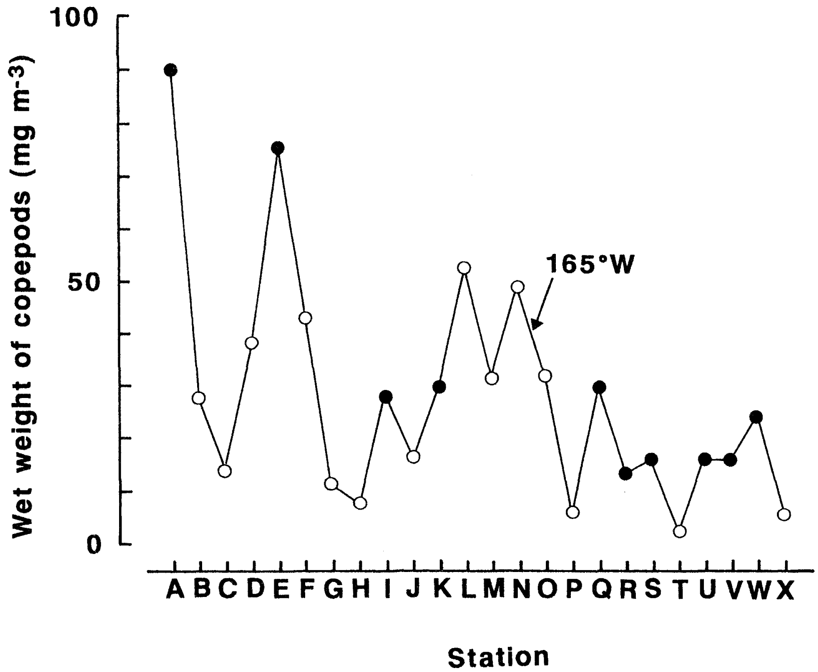

Fig. 7 Variations in the wet weight of copepods obatined by the Norpac net operations from a depth of 150 m to the surface nearby the stations for CTD casts.Alphabetic stations indicate the stations for CTD casts. ○ : daytime observations ; ● : twilight and nighttime observations.

total primary productivity (Fig. 5b). The 2–10 or <2 μm fraction dominated total primary productivity at the remaining stations.

The biomass of living phytoplankton may have much influence on the spatial variations of the primary productivity. Using chlorophyll *a* concentration as an index of phytoplankton biomass, the chlorophyll *a*-specific productiv-

Table 1. Mean ± standard deviation (σ_{n-1}) of wind velocity, solar radiation, temperature, salinity, nitraite + nitrate concentration, depth of mixed layer and wet weight of copepods in the western and central subarctic North Pacific (W &CSNP) and the eastern subarctic North Pacific (ESNP). The n indicates the number of data for calculating the mean ± standard deviation. Mann-Whitney U-test (two-tailed test) was used to test significance in the parameters between the W & CSNP and ESNP.

	W & CSNP	ESNP	Significance
Wind velocity (m s^{-1})	12.2±4.4 (n=1864)	9.7±3.9 (n=1136)	P<0.0001
Solar radiation (mol quanta m^{-2} d^{-1})	8.2±3.3 (n=13)	5.2±2.5 (n=8)	P>0.08
Temperature (℃)	7.1±2.3 (n=11)	7.9±1.7 (n=8)	P>0.1
Salinity	33.245±0.422 (n=11)	32.932±0.127 (n=5)	P>0.2
Nitrite+nitrate (μM)	14.6±4.4 (n=11)	11.3±5.1 (n=8)	P>0.05
Depth of mixed lager (m)	102±26 (n=14)	101±9 (n=10)	P>0.05
Wet weight of copepods (mg m^{-3})	35.9±24.6 (n=13)	19.2±13.7 (n=11)	P>0.05

ity (P^B) can be taken as an index of the growth rate (e.g., LALLI and PARSONS, 1993). The variations of the P^B of the total and <2 μm fraction along the eas-west sampling tract were roughly constant, but those of the 2–10 and 10–200 μm fractions were scattered (Fig. 6). High values tended to be found after Stn. 11 for the total and every size fraction.

Copepods are important grazers of phytoplankton. The wet weight of copepods obtained by the Norpac net operations ranged from 2.3 to 90.3mg m^{-3} (Fig. 7). High wet weights exceeding 40 mg m^{-3} were found at stations in the region west of 165° W, a pattern which is similar to those of the chlorophyll *a* concentration and primary productivity.

4. Discussion

High total chlorophyll *a* concentrations and primary productivity were observed at the surface west of 165° W, that is, in the western and central subarctic North Pacific (W & CSNP), with one exception (high primary productivity at Stn. 16) (Figs 4 and 5). Large phytoplankton, the 10–200 μm fraction, usually contributed to the high total chlorophyll *a* concentrations and often primary productivity. The P^B of the large phytoplankton were not significantly different between the stations dominated by large phytoplankton with high total chlorophyll *a* concentrations (Stns. 6, 7, 9 and 11) and the remaining stations with relatively low total concentrations (Stns. 3–5, 8, 10 and 12–18) (U-test, P>0.05, two-tailed test). This implies that the environmental conditions were advantageous for the survival of the large phytoplankton in the W & CSNP compared with those in the eastern subarctic North Pacific (ESNP).

Most of the stations in the W &CSNP were located at more southern area compared with the stations in the ESNP (Fig. 1). There is thus the possibility that the high-W & CSNP and low ESNP contribution of large phytoplankton to phytoplankton chlorophyll *a* concentration and primary productivity included a latitudinal effect. In the W &CSNP, the chlorophyll *a* concentrations at Stn. 1 (southernmost station) and Stn. 11 (northernmost station) were high and almost equal (Fig. 4). This indicates less likelihood of the latitudinal effect on distribution.

Daily solar radiation, temperature, salinity, mixed layer depth and nitrite + nitrate concentrations were not significantly different between the W &CSNP (between November 28 and December 10) and ESNP (December 11–18) (U-test, P>0.05, two-tailed test ; Table 1). The wet weights of the copepods were not significantly different between daytime observations and twilight and nighttime observations in the W &CSNP and ESNP (U-test, P>0.1). We thus compared the wet weight of the copepods between the W &CSNP and ESNP using all of the data. No significant difference was noticed between the estimates from two regions (U-test, P>0.05). In contrast, wind velocity was identified to be significantly different between the two regions (P<0.0001), and the mean value in the W & CSNP was higher than that in the

ESNP (Table 1). Wind velocity tended to be higher in the W&CSNP than in the ESNP.

The high-W&CSNP and low-ESNP trend in wind velocity results in more intense vertical mixing of the water in the surface layer in the W&CSNP compared with that in the ESNP. It has been shown through field bag experiments (EPPLEY *et al.*, 1978 ; GRICE *et al.*, 1980 ; DAVIS, 1982) and simulation (TAYLOR and JOINT, 1990) that intense mixing of the water favors large cells. We thus suggest that the more intense wind stress in the W&CSNP was advantageous for the survival of large phytoplankton in the surface layer. Based on long-term observations, high-west and low-east trend in wind stress for stirring upper oceans was established in a previous study in the North Pacific in winter (HELLERMAN and ROSENSTEIN, 1983). Thus, the occurrence of high total chlorophyll *a* concentration and primary productivity due to large phytoplankton in the W&CSNP seems to be a characteristic of the subarctic North Pacific in winter.

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