Primary productivity and photosynthetic features of phytoplankton in the Sea of Okhotsk during late summer

Tomonori Isada[1], Koji Suzuki[1], Hongbin Liu[2], Jun Nishioka[3] and Takeshi Nakatsuka[3]

[1] Graduate School of Environmental Science and Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan. E-mail: t-isada@ees.hokudai.ac.jp
[2] Department of Biology Atmospheric, Marine and Coastal Environment (AMCE) Program, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
[3] Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan

Introduction

The Sea of Okhotsk is considered to be one of the most biologically productive regions in the world's oceans, especially on the continental shelf (Saitoh *et al*., 1996; Sorokin and Sorokin, 1999), and that supports high fisheries production. The Sea of Okhotsk, which is located in the northwestern Pacific rim, is one of the largest marginal seas in the world and is also characterized as a region where seasonal sea ice reaches the lowest latitudes (Kimura and Wakatsuchi, 2000). When sea ice is formed on the northwestern continental shelf in winter, a large amount of cold brine water is rejected. The brine water sinks to the bottom of the shelf and forms dense shelf water (DSW). Since the DSW has a large amount of resuspended particles due to strong tidal mixing on the shelf (Kowakik and Polyakov, 1998), the outflow of DSW results in a large flux of particles from the shelf to the open ocean (Nakatsuka *et al*., 2002). Furthermore, time-series sediment trap experiments in the western region of the Sea of Okhotsk revealed that biogenic and lithogenic particles are exported to the open ocean interior by an intermediate water flow (Nakatsuka *et al*., 2004). These previous studies suggested that DSW containing these particles contributes to lateral material transport and biological productivity. The Amur River, which is one of the largest rivers of eastern Eurasia, is also thought to play an important role as the major source of terrestrial organic matter to the Sea of Okhotsk, and of nutrients for phytoplankton growth (Nakatsuka *et al*., 2004). Strong tidal currents also affect nutrient distributions in the Sea of Okhotsk (Andreev and Pavlova, 2009). However, little is known about primary productivity and its controlling factors, especially after the spring blooms. Therefore, we examined primary productivity and photosynthetic features of phytoplankton in the Sea of Okhotsk during August and September 2006.

Methods

Seawater samples were collected from 17 stations on board the Russian R/V *Prof. Khromov* (Kh06 cruise) from August 13 to September 14, 2006 (Fig. 1). Samples for chlorophyll (Chl) *a* concentration and primary productivity using simulated *in situ* incubation over a day were obtained from the surface (1 m depth), and relative 60, 30, 10, 5 and 1% light depths (where relative light intensity in the sea surface was defined as 100%). Similarly, samples for the photosynthesis–irradiance (P – E) experiment, Chl-specific absorption coefficient of phytoplankton

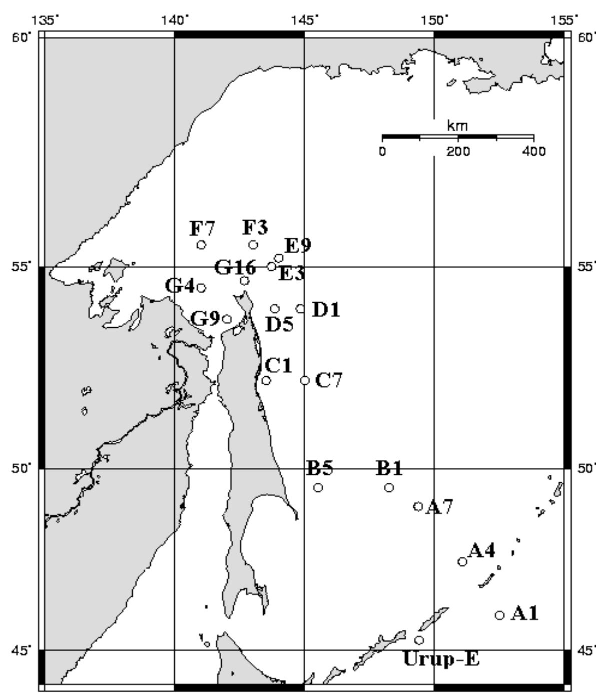

Fig. 1 Sampling stations in the Sea of Okhotsk during the cruise from August 13 to September 14, 2006 (open circles).

and size-fractionated Chl-*a* (microplankton: > 10 µm, nanoplankton: 2–10 µm and picoplankton: < 2 µm) were obtained from the surface and relative 5% light depth. Chl-*a* concentration was estimated by using a Tuner Designs 10-AU fluorometer. Photosynthetic rate was estimated with a ^{13}C tracer technique (Hama *et al*., 1983).

Results and Discussion

Chlorophyll *a* concentration

Chl-*a* concentrations were generally high in coastal waters near Sakhalin Island (Fig. 2). In particular, high Chl-*a* concentrations were observed in the continental shelf of Sakhalin (Station (Stn) C1) and Sakhalin Bay (Stn G9), and were 9.7 and 13 mg m^{-3}, respectively. Higher Chl-*a* concentrations were also found near Stns C1 and G9 in the previous study of Sorokin and Sorokin (1999). Similar temporal–spatial patterns were found in the composition of large-sized (> 10 µm) phytoplankton to the total. On the other hand, Chl-*a* concentrations in open waters were relatively low (< 1 mg m^{-3}).

Primary productivity

During our cruise, surface primary productivity and depth-integrated daily primary production within the euphotic layer ranged from 7 to 753 mg C m^{-3} d^{-1} and from 74 to 1,986 mg C m^{-2} d^{-1}, respectively. Higher surface primary productivity, as well as the Chl-*a* distribution, was observed at Stns C1 and G9 (Fig. 3). These values were within the ranges reported previously in the study area during early summer (Sorokin and Sorokin, 1999). The surface primary productivity correlated significantly with Chl-*a* concentration (R = 0.84, n = 17, P < 0.001), but not sea surface temperature, solar light intensity (photosynthetic available radiation; PAR) or nutrient concentrations. These results indicate that surface primary productivity in this study period largely depended on the phytoplankton biomass.

Photosynthetic parameters

We also estimated maximum quantum yield of carbon fixation in photosynthesis ($\Phi_{c\ max}$; mol C mol photon^{-1}) from the initial slope of the P – E curve and the mean specific absorption coefficient of phytoplankton. $\Phi_{c\ max}$ is an index of light utilization efficiency in photosynthesis. Higher values of surface $\Phi_{c\ max}$ were found in the continental shelf of Sakhalin and Sakhalin Bay (0.061 and 0.086 mol C mol photon^{-1}, respectively), as well as the Chl-*a* concentration and primary productivity. On the other hand, surface $\Phi_{c\ max}$ was relatively low in the pelagic region. According to Bannister (1974) and Babin *et al*. (1996), $\Phi_{c\ max}$ for natural algal communities in optimum physiological conditions was about 0.06

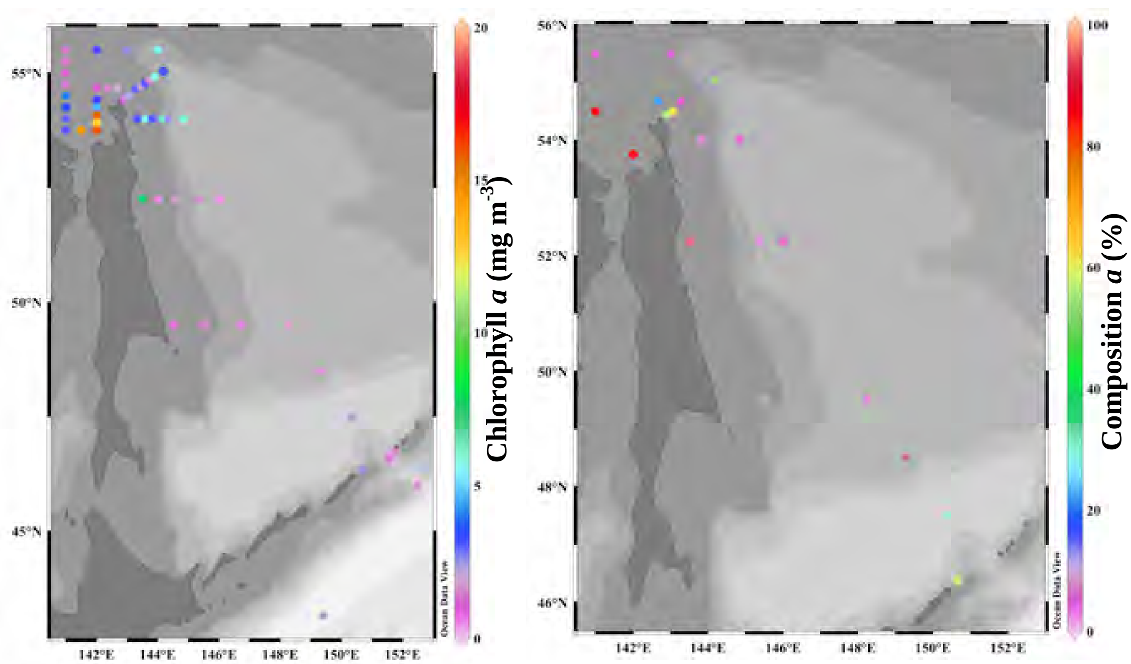

Fig. 2 Results of chlorophyll *a* concentration (left-side figure) and composition of micro-sized (> 10 µm) phytoplankton to the total (right-side figure).

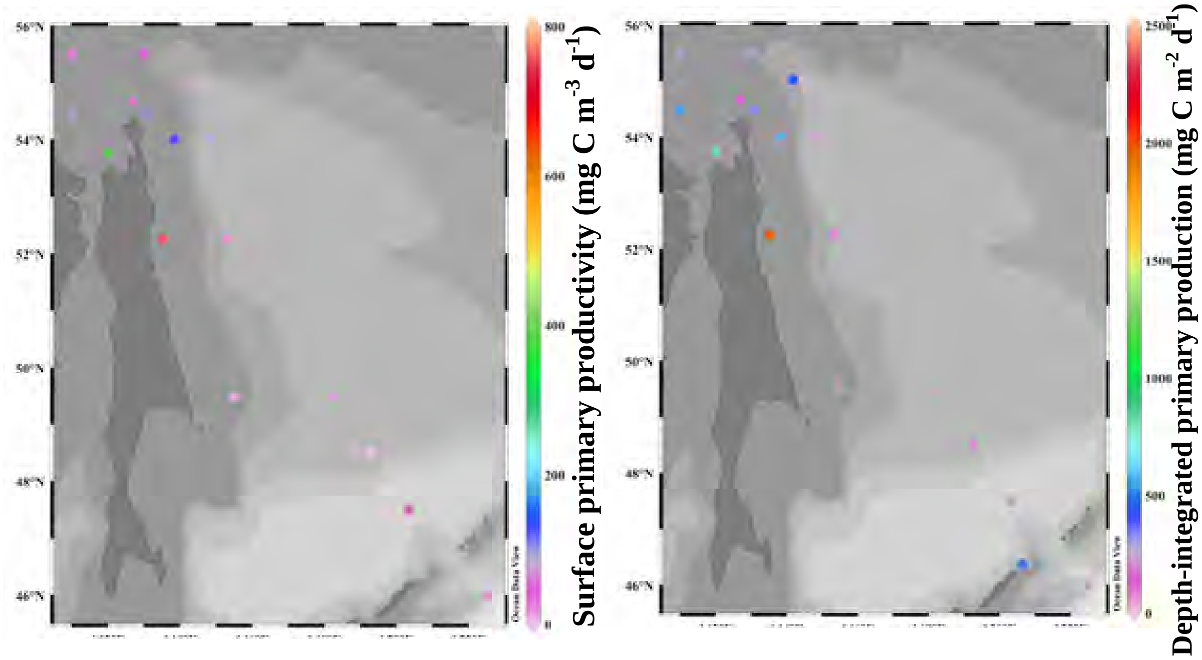

Fig. 3 Results of surface primary productivity (left-side figure) and depth-integrated primary production within the euphotic layer (right-side figure).

to 0.08 mol C (mol photon)$^{-1}$. Therefore, the data obtained at Stns C1 and G9 show that phytoplankton groups had higher light utilization efficiency in photosynthesis and that lower values in open waters might be caused by nutrient limitation. In fact, the F_v/F_m, which is the photochemical quantum efficiency of algal photosystem II (PSII) and is an index of nutrient (nitrate or Fe) limitations (Green *et al*., 1992), was lower in the pelagic region, as measured with pulse amplitude modulated (PAM) fluorometry, but increased after the addition of nutrients (Liu *et al*., 2009). Although no significant relationships were found between photosynthetic parameters, including $\Phi_{c\ max}$ at the surface and both sea surface temperature and macronutrient levels, surface $\Phi_{c\ max}$ correlated with Chl-*a* concentration (R = 0.94, n = 17, P < 0.001). These results indicate that the phytoplankton groups with high abundance possessed high $\Phi_{c\ max}$ in the study area.

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