Effects of a seamount on phytoplankton production in the western Pacific Ocean

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Abstract—Spatial distributions of nitrate, phosphate and chlorophyll were investigated in relation to the velocity field in the vicinity of Komahashi No. 2 Seamount in the northern part of Kyushu Palau Ridge of the western Pacific Ocean. Topography-current interactions above the seamount induced perturbations in nutrient distributions, leading to enhanced upward transport of nutrients into the base of the euphotic zone. The enrichment was occasionally accompanied by elevated amounts of chlorophyll a downstream of the seamount. The increase was most pronounced in the subsurface chlorophyll maximum layer, but occasionally effects were observed near the surface. The appearance of the high chlorophyll a patch in the lower euphotic zone seemed to be dependent on the velocity field with homogeneous flow leading to enhanced chlorophyll a. Vertical or horizontal shear flow was not associated with high chlorophyll a, possibly because physical dispersion of nutrients occurred faster than phytoplankton utilization. Since the population of seamounts is quite numerous, enhancement of upward advection of nutrients into the euphotic zone over the seamounts is likely quite important in basin-scale carbon budget, especially in the new production.

INTRODUCTION

The global map of primary production and CZCS (Coastal Zone Color Scanner) images of chlorophyll reveal wide-spreading low productive areas in ocean-basin scales and relatively high productivity areas in the proximity of land masses, in upwelling regions and at high latitudes coinciding with areas of high nutrient supply to the euphotic zone (BERGER et al., 1987; FELDMAN, 1989). The areas of low production and biomass, once called biological deserts, are found where strong stratification prevails during most part of the year. Thus, the regional difference in both productivity and chlorophyll abundance can be primarily ascribed to difference in magnitude of ambient nutrient supply (BERGER et al., 1987). In oligotrophic areas of low biomass and production, primary production is mainly fueled by regenerated nutrients. However, episodic inputs of nutrients into the euphotic zone caused by physical events, such as storm-induced mixing and upwelling, enhance productivity and phytoplankton biomass of oligotrophic waters (DITULLIO and LAWS, 1991). Degree and frequency of the episodic input are important factors that determine magnitude of total annual production (GOLDMAN, 1988). Such physical events fre-

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quently occur around islands: interactions between velocity field and island produce elevated vertical mixing and von Karman eddies which induce upward transport of nutrients into the euphotic zone (Lafond and Lafond, 1971; Barkley, 1972). A consequence is enhanced local biological production, called the island effect (Doty and Oguri, 1956; Takahashi et al., 1980).

Seamounts are also known to modify oceanic velocity field and to alter the intensity of density stratification. Seamounts are submerged volcanoes that occur singly or in groups. The interaction between seamounts and ocean current affects various physical processes, including acceleration of flow with compressed streamline, deflection of isotherms, eddy formation and trapping, bottom intensified Taylor columns and internal wave reflection (Rodén, 1987). These physical disturbances affect biological processes over seamounts by enhancing upward transport of nutrients and by entrapping both autochthonous and allochthonous pelagic organisms within semi-enclosed eddies formed over seamounts (Boehlert and Genin, 1987). Thus, seamounts are of importance in biological productivity in the ocean, particularly in the oligotrophic waters where strong stratification prevails in the upper layer. Seamounts are ubiquitous geotopographic features of the world ocean basin, but are particularly common in the Pacific Ocean where estimated to contain more than 30,000 seamounts (Smith and Jordan, 1988). Therefore, physical effects of seamounts and their biological consequences have potential significance in ocean-basin scale primary production.

Kozlov et al. (1982) first reported elevated levels of nutrients due to upwelling above several seamounts in the Pacific. They found the effect reached the surface layer with higher silicate concentration than in the surrounding areas. Upwelling and nutrient enrichment in the lower part of euphotic zone have been documented also in Wanganella Bank (Darnitsky et al., 1984) and Minami-Kasuga Seamount (Genin and Boehlert, 1985).

Previous studies do not present a consistent view on the effect of seamounts on lower food chain processes. In some cases positive effects, that is, higher amounts of chlorophyll a and ATP were found above seamounts than in adjacent oceanic areas (Genin and Boehlert, 1985; Lopukhin, 1986; Lopukhin and Benzhytsky, 1986). These authors ascribed the positive effects to the upwelling above the seamounts. In other cases, the positive effects were not present or were obscure in chlorophyll a (Genin and Boehlert, 1985), primary production (Sorokin, 1987), bacterial biomass and production (Sorokin and Sorokina, 1985; Cho, 1991) and zooplankton biomass (Rudyakov and Timonin, 1986; Voronina and Timonin, 1986). The variable degree of the biological effects as seen in literature is due mainly to the variability of spatial extent and duration of the upwelling, which depends on a variety of topographic and flow parameters that are time varying and spatially non-uniform (Rodén, 1987). Furthermore, since the primary effects are nutrient enrichments by upwelling and entrapment of the organisms by eddy formation above seamounts, other biological effects should be variable, because organisms respond differently and at different rates to nutrient enrichment. Repeated visits to particular seamounts confirmed the transient nature of upwelling events above seamounts (Darnitsky et al., 1984; Genin and Boehlert, 1985).
At present, biological consequences of the physical perturbations in the vicinity of seamounts are not well understood. One of the major constraints is that the physical processes around the seamounts are not well described. Most studies were based on a single, or only a few visits to particular seamounts. To date, no investigation on biological effects of seamounts on phytoplankton dynamics in relation to the velocity field based on repeated observation of a particular seamount has been published. The purpose of our study was to document velocity field, spatial distributions of nutrients and chlorophyll $a$ and size composition of phytoplankton biomass in the vicinity of Komahashi No. 2 Seamount to assess relationship between velocity field and chlorophyll distributions and spatial scales of the effect of the seamounts. We present descriptions of spatial distributions of biological parameters, and detection of their differences between over seamounts and adjacent oceanic areas as a “first order” study in the region. Since the biological effect of upwelling is expected to be most apparent in the subsurface euphotic zone rather than the near surface above seamounts (GENIN and BOEHLERT, 1985; LOPUKHIN, 1986), we conducted shipborne observations around the seamount to detect the effects.

Komahashi No. 2 Seamount (or Komahashi Daini Kaizan) is located at 29°52' N, 133°18' E in the northern part of Kyushu Palau Ridge. The seamount has an elliptic shape in the upper 2300-m depth and its summit is 289 m deep (Fig. 1). The Kuroshio current flows approximately 70 to 180 km away northwestward from the seamount (DEPARTMENT OF HYDROGRAPHY, 1989, 1990, 1991, 1992, 1993). The study area is characterized by oligotrophic subtropical water with undetectable or low nitrate of <0.1 $\mu$M near the surface, and by distinct subsurface chlorophyll maximum in the lower part of the euphotic zone (FURUYA and MARUMO, 1983;
Takahashi et al., 1985). An anticyclonic gyre with a diameter of <100 km occasionally is reported to exist in the east of the seamount (Sugimoto et al. 1986), and the seamount can be located in the margin of the eddy.

MATERIALS AND METHODS

Field observations were made in May, June, July, September and October using the T/S Seisui Maru or R/V Tansei Maru (Table 1). On arriving at the study site the current direction and velocity was horizontally surveyed by an acoustic Doppler current profiler (CI-20, Furuno Co.) at three depths: one within the mixing layer (usually 50 m or 75, 80 m), the others in the thermocline (100 m) and below it (150 m). After the survey, CTD/rosette sampler casts down were used to sample both upstream and downstream sides of the seamount. Lengths of transects were variable among cruises. Water samples were collected from 13 layers in the upper 150- to 300-m depths with Niskin bottles and a bucket during the upcast of the CTD (Neil Brown, MK-IIIB). The distance between neighboring sampling stations varied from 2 to 18 km. Generally, stations were most closely spaced around the seamount. A drifting buoy experiment was conducted during SE-93-7 cruise (Table 1). The buoy, fitted with a wind-shade drogue at 85-m depth where subsurface chlorophyll maximum occurred, was deployed at 30°1.8' N, 133°25.5' E and followed for 24 hours. During the tracking CTD-rosette samplings were conducted in the upper 300 m every two hours.

Chlorophyll a was determined during all the cruises fluorometrically (Turner Design, 10R) for N,N-dimethylformamide extract of particles retained on Whatman GF/F filters (Yentsch and Menzel, 1963; Suzuki and Ishimaru, 1990). The fluorometer was calibrated using pure chlorophyll a (Sigma Chem.). Each vertical profile of chlorophyll a was examined by fitting to the generalized formula proposed by Platt et al. (1988) and modified by Matsumura and Shiomoto (1993). The model is a Gaussian curve to represent a chlorophyll maximum superimposed on a

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Date</th>
<th>Stations</th>
<th>Subsurface currents</th>
</tr>
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<tbody>
<tr>
<td>SE-89-7</td>
<td>July 14-15, 1989</td>
<td>14</td>
<td>Northwestward, homogeneous horizontal flow</td>
</tr>
<tr>
<td>SE-89-8</td>
<td>July 22-23, 1989</td>
<td>15</td>
<td>Northward, vertical and horizontal shear flow</td>
</tr>
<tr>
<td>SE-89-12</td>
<td>Sept. 18-21, 1989</td>
<td>8</td>
<td>Southwestward, homogeneous horizontal flow</td>
</tr>
<tr>
<td>SE-90-3</td>
<td>May 19-21, 1990</td>
<td>24</td>
<td>Anticyclonic eddy over the seamount</td>
</tr>
<tr>
<td>SE-90-7</td>
<td>July 21-23, 1990</td>
<td>14</td>
<td>South- to southwestward, vertical shear flow</td>
</tr>
<tr>
<td>KT-91-8</td>
<td>June 19-21, 1991</td>
<td>19</td>
<td>Westward, homogeneous horizontal flow</td>
</tr>
<tr>
<td>SE-92-10</td>
<td>July 26, 1992</td>
<td>7</td>
<td>North- to westward, vertical and horizontal shear flow</td>
</tr>
<tr>
<td></td>
<td>Aug. 1, 1992</td>
<td>7</td>
<td>Northward, homogeneous flow</td>
</tr>
<tr>
<td>SE-93-7</td>
<td>June 17-19, 1993</td>
<td>19</td>
<td>West- to southwestward, sheared flow above the summit</td>
</tr>
</tbody>
</table>
background concentration that decrease linearly with depth:

\[
B(z) = B_0 + c \cdot z + \frac{h}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(z - z_m)^2}{2\sigma} \right)
\]  

(1)

where \(B(z)\) and \(B_0\) are the concentration of chlorophyll \(a\) (\(\mu g\) L\(^{-1}\)) at depth \(z\) (m) and in the surface, respectively, \(c\) is the slope of background concentration along with depth (\(\mu g\) L\(^{-1}\)m\(^{-1}\)), \(z_m\) is the depth of the chlorophyll maximum, \(h/(\sigma \sqrt{2\pi})\) is the height of the maximum (\(\mu g\) L\(^{-1}\)) on the background, and \(\sigma\) determines the width of maximum (four \(\sigma\) is the approximate width).

Nitrate and nitrite were determined on board ship (SE-89-7, -8, -12) or in land laboratory for frozen samples (KT-91-8, SE-92-10, -93-7) with a Technicon AutoAnalyzer (GLIBERT and LODER, 1977), and phosphate manually (PARSONS et al., 1984). Nitrite was not always determined separately from nitrate. Since nitrite has never been a significant component of nitrate plus nitrite in the study area, we refer to nitrate plus nitrite as nitrate hereafter. Nutrients were not available during SE-90-3, SE-90-7 and SE-91-11 cruises. Phosphate was measured during KT-91-8 and SE-93-7 cruises. Vertical profiles of photosynthetically available radiation were measured with a spherical quantum sensor (Li-Cor, LI-193SB) to calculate the depth of 1% irradiance of that just below the surface. An OCTOPUS, a multiparametric underwater sensor system (ISHIMARU et al., 1984) was used for measurement of light fields during KT-91-8 cruise.

RESULTS

The velocity field was categorized tentatively as horizontally homogeneous or sheared flow based on current velocity and direction as observed by the ADCP: the velocity field with a variation of current direction within 90 degree either vertically or horizontally, and difference in velocity within a factor two was arbitrarily termed as homogeneous and that exceeding 90 degree as sheared flow (Table 1). For example, as described below, the velocity field during SE-89-7 cruise was homogeneous, while that during SE-89-8 was sheared. During some cruises the velocity field changed temporally. In that case, the comments on the currents in Table 1 were based on those at the water sampling.

July 1989

A northward current with velocity of >50 cm s\(^{-1}\) was observed at 100- and 150-m depths on the northwestern side of the seamount. On the opposite side, the current was weaker (<50 cm s\(^{-1}\)) but with a similar current direction, except at southermmost station (Sta. 14) (Fig. 2a). The overall current velocity and direction were similar between 100- and 150-m depths, showing there was a rather homogeneous velocity field in the subsurface layer. Eight days later, the velocity field changed considerably (Fig. 2b). Although north- to northwestward current dominated at 100-m depth in the
Fig. 2. Subsurface currents at 100- and 150-m depths during (a) SE-89-7, (b) SE-89-8 and (c) SE-90-3 cruises. In the top and middle panels thick broken lines that run northeast and southwest near the summit divide stations into upstream (southern area) and downstream (northern area) sides according to flows at the 100-m depth.
northwestern side of the summit, currents with southern component existed above the summit. The current changed directions between 100- and 150-m depths, indicating a vertical as well as horizontal shear in the subsurface layer. On the basis of the distribution of the current direction at 100-m depth, stations were grouped into either upstream or downstream sides along the axes of flow direction (Figs. 2a and 2b).

An uplift of 2- to 7-μM isolines of nitrate was found above the seamount below 150-m depth during the SE-89-7 cruise (Fig. 3a). The isoline of 1 μM penetrated into the 1% light level of 95-m depth. There was another uplift of the isoline at Station 2, which was located in the eastern flank and neither downstream nor upstream. Eight days later, nitrate isolines were still uplifted above the summit (Fig. 3b). The isolines tended to rise upward in the downstream direction as observed at Stns. 6, 7, 11 (Fig. 3b). Temperature fields were also perturbed above the seamount during both cruises: a dome-like uplift of isotherms at depths of 900 to 1100 m during SE-89-7 cruise, and a coherent uplift of the isotherm at the depths of 1250–1550 m downstream. However, these temperature structures decayed along with decreasing depths and did not penetrate into the upper 300-m layer.

During SE-89-7 cruise, the amount of chlorophyll a was significantly higher in the downstream than in the upstream side throughout the upper 200-m water column (Table 2). Chlorophyll a was 1.4 and 2.9 times higher downstream at the 75 to 100-m and at the 100 to 125-m depths, respectively. Surface concentrations were also

<table>
<thead>
<tr>
<th>Layer (m)</th>
<th>Integrated chlorophyll a (mg m⁻²)</th>
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<tbody>
<tr>
<td></td>
<td>Upstream (n=6)</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SE-89-7 cruise</strong></td>
<td></td>
</tr>
<tr>
<td>0–25</td>
<td>3.9±0.90*</td>
</tr>
<tr>
<td>0–70</td>
<td>12.5±2.26*</td>
</tr>
<tr>
<td>70–100</td>
<td>6.1±0.27*</td>
</tr>
<tr>
<td>100–125</td>
<td>1.0±0.12*</td>
</tr>
<tr>
<td>0–200</td>
<td>21.4±2.26**</td>
</tr>
<tr>
<td><strong>SE-89-8 cruise</strong></td>
<td></td>
</tr>
<tr>
<td>0–25</td>
<td>5.6±2.42</td>
</tr>
<tr>
<td>0–70</td>
<td>24.8±7.99</td>
</tr>
<tr>
<td>70–100</td>
<td>13.2±4.02*</td>
</tr>
<tr>
<td>100–125</td>
<td>3.9±2.11</td>
</tr>
<tr>
<td>0–200</td>
<td>49.6±10.48</td>
</tr>
</tbody>
</table>

*Significant at $p \leq 0.05$, **$p \leq 0.01$.
higher on the downstream side (Table 2). At 100-m depth that approximately coincided with the 0.8- to 1-% light depth, the upstream side was characterized by higher nitrate and lower chlorophyll $a$, while the downstream side by lower nitrate and higher chlorophyll $a$, indicating an increase of chlorophyll $a$ with consumption of ambient nitrate (Fig. 4). Based upon changes in concentration of chlorophyll $a$ shown in Fig. 4 and current velocity of 25 cm$^{-1}$ s$^{-1}$, and assuming exponential growth, the specific growth rate was calculated:

$$\text{specific growth rate} = \ln(C_i/C_f)/(d_{ij}/v),$$

where $d_{ij}$ is distant between Stns. $i$ and $j$, $v$ is current velocity, and $C_i$ and $C_f$ are
chlorophyll \( a \) concentration at Stns. \( i \) and \( j \), respectively. Growth rates were 0 d\(^{-1}\) between Stns. 11 and 10, 0.28 d\(^{-1}\) between Stns. 11 and 9, and 0.17 d\(^{-1}\) between Stns. 11 and 8.

In contrast to conditions during SE-89-7, downstream chlorophyll \( a \) concentrations were not higher during SE-89-8 cruise (Table 2). In fact, the downstream layer of 70- to 100-m depth had significantly lower amount than upstream.

**May 1990**

Current directions at 100- and 150-m depths showed an anticyclonic circulation above the summit (Fig. 2c), indicating a closed eddy. The closed eddy was observed only in this period in the present study. A distinct deflection of isotherms was
observed over the seamount and this penetrated into the upper 300-m water column (Fig. 3c). A patch of high chlorophyll a concentration of >0.6 μg L\(^{-1}\) was found at 50- to 85-m depths over the seamount. Such high concentrations are unusual in the area south of Kuroshio (HARASHIMA and KIKUCHI, 1990). The depth zone of high chlorophyll a concentrations was above the 1% light depth, 89 to 91-m depth. Maximum concentration within the patch was 2.1 μg L\(^{-1}\) at 70-m depth of Stn. 9, the highest chlorophyll a concentration we observed during our seamount study. Although data on nutrients were not available, the chlorophyll a patch was probably in response to nutrient enrichment.

June 1991

The velocity field was homogeneous in the subsurface layer in June 1991 (Fig. 5). The currents at 100- and 150-m depth were approximately westward. Above the seamount top and in the southwestern flank, the current velocity was accelerated to 75 cm s\(^{-1}\) as its maximum, more than twice the speed of the current upstream of the seamount of the upstream velocity. Current direction on the northern and southern side strongly suggests a divergence around the seamount.

The 18 to 20°C isotherms rose to depths of 60 to 200-m southwestward from the summit. In accordance with the temperature distribution, isolines of both nitrate and phosphate were elevated atop the summit (Stns. 16 and 16') or on the southwestern side (Fig. 5). The 1-μM nitrate isoline penetrated above 1% light depth which varied from 84 to 96 m. Chlorophyll a concentration at subsurface chlorophyll maximum was <0.3 μg L\(^{-1}\) just above the seamount top, but was >0.4 μg L\(^{-1}\) on the northern
Fig. 5. Currents at 100-m depth (top) and vertical profiles of nitrate (middle) and phosphate (bottom) during KT-91-8 cruise. Broken lines denote depths of 1% irradiance of that just below the surface.

(Stns. 18, 19 and 20), southern flanks (Stns. 11 and 12) and downstream of the seamount (Stns. 26 and 27).

June 1993

The subsurface current was westward at 75-m depth and southeastward at 150 m above the seamount top, causing vertical shears in the velocity field both horizontally and vertically around the summit (Fig. 6). However, in the southwestern flank away from the summit the current was homogeneously southwestward. An
Fig. 6. Currents at 75- and 150-m depth (top) and vertical profiles of nitrate (upper middle) and phosphate (lower middle) and chlorophyll $a$ (bottom) during SE-93-7 cruise. Broken lines denote depths of 1% irradiance of that just below the surface.

anticyclonic eddy was developed in the east of the study site during this period (DEPARTMENT OF HYDROGRAPHY, 1993). The Komahashi No. 2 Seamount was in the fringe of the eddy whose flow was expected to have a north component. Nonetheless the observed current near the surface was opposite, that is, west to southwestward. After making observations along the transect from southwest to
southeast, a drifter was deployed near Stn. 6. The buoy drifted southwestward just along the transect at a velocity of 15.5 km per 24 hours. During the buoy tracking, velocity of the subsurface current did not vary much, and was around 15 to 20 cm s\(^{-1}\), and a rapid current of >50 cm s\(^{-1}\) that had been found half a day before over the summit was not observed, indicating the transient feature of velocity field at that time.

Isolines of temperature, nitrate and phosphate were uplifted at Stn. 5 on the top of the seamount, indicating an upwelling (Fig. 6). Below the 200-m depth, the N:P ratio of the upwelled water was approximately 16, and this ratio did not change up to the 100-m depth. However, at 80-m depth, where the subsurface chlorophyll maximum was located, the ratio decreased to <11, suggesting an active uptake of nitrate. The nitrate isoline of 1 µM was above 95-m depth which was at 1% light level. Another distinct uplift of isolines of phosphate and nitrate existed in the northeastern side of the seamount.

Chlorophyll \(a\) concentration in the subsurface layer was relatively low atop the summit. Higher chlorophyll \(a\) concentrations than that above the summit were observed upstream and particularly, on the downstream side of the seamount, suggesting phytoplankton growth in response to nutrient enrichment at the base of the euphotic zone (Fig. 6).

Other cruises

Subsurface currents had a western component during the other cruises (Table 1). In general, temperature isotherms were perturbed above the summit of the seamount. Nitrate concentrations above the seamount and downstream varied from below the detection limit to five µM at the 1% light depth. In the upstream nitrate was exhausted at or above the 1% light depth. Downstream enhancement of chlorophyll amount was observed during SE-89-12 and SE-91-11 cruises, whereas chlorophyll concentrations were unaffected during SE-90-7 and SE-92-10 cruises.

Distributions of chlorophyll \(a\)

All chlorophyll-\(a\) profiles were characterized by a distinct subsurface chlorophyll maximum both upstream and downstream. Relatively high concentrations were observed on the downstream side of the seamount under vertically and horizontally homogeneous flow conditions, while the enhancement was not obvious when vertical or horizontal shear in the subsurface velocity fields occurred. When the velocity field was homogeneous, concentrations of chlorophyll \(a\) at the subsurface chlorophyll maximum tended to be low atop the summit, but higher in downstream direction (Figs. 4 and 5). In contrast, in velocity fields with either vertical or horizontal shears, downstream subsurface chlorophyll maximum layers did not have anomalously high chlorophyll \(a\) concentrations. An exception was June 1993, when there were shears above the seamount and a homogeneous flow in downstream direction, and subsurface chlorophyll \(a\) concentrations was higher on downstream side than upstream (Fig. 6).

Upstream and downstream chlorophyll \(a\) profiles were compared for all cruises,
except those during SE-90-3 cruise when the closed eddy was formed above the seamount (Fig. 7). During the latter cruise, high concentrations of >0.4 μg L\(^{-1}\) in the downstream side and over 0.3 μg L\(^{-1}\) were due to mass occurrence of blue-green alga *Trichodesmium erythraeum* and *T. thiebautii*. These higher concentrations than 0.4 μg L\(^{-1}\) in the surface were excluded in the curve fitting to parametrize the vertical profiles. There were significant differences in the vertical profiles of chlorophyll \(a\) between downstream and upstream sides based on parameters obtained by fitting \((r^2 > 0.92)\) each profile to Eq. (1) (Table 3). The integrated amount in the 30-m water

![Graph showing cumulative vertical profiles of chlorophyll a in downstream and upstream sides.](image)

**Fig. 7.** Cumulative vertical profiles of chlorophyll \(a\) in downstream (left) and upstream side (right) of subsurface current over Komahashi No. 2 Seamount. Data were combined from all the cruises listed in Table 1 except SE-90-3 cruise.

**Table 3.** Comparison of vertical profiles of chlorophyll \(a\) downstream and upstream in the vicinity of Komahashi No. 2 Seamount. Values are mean and one SD

<table>
<thead>
<tr>
<th></th>
<th>Downstream (n=64)</th>
<th>Upstream (n=51)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface concentration ((B_0)) ((\mu g L^{-1}))</td>
<td>0.13±0.05</td>
<td>0.11±0.068</td>
</tr>
<tr>
<td>Peak depth of subsurface chlorophyll maximum ((z_m)) ((m))</td>
<td>78.8±12.6*</td>
<td>86.5±10.5*</td>
</tr>
<tr>
<td>Integral from 15-m above to 15-m below the peak depth ((mg m^{-2}))</td>
<td>10.7±3.1***</td>
<td>8.0±1.7***</td>
</tr>
<tr>
<td>A quarter of the width of the maximum ((\alpha)) ((m))</td>
<td>18.1±5.9**</td>
<td>23.6±7.1**</td>
</tr>
</tbody>
</table>

*Significant at \(p < 0.05\), **\(p < 0.01\), ***\(p < 0.005\).
column around the subsurface chlorophyll maximum was calculated using Eq. (1). In the downstream side the subsurface chlorophyll maximum was located shallower with higher amount of chlorophyll a than in the upstream side, where the shape of the maximum was more diffused with a larger $\sigma$ on the average. Downstream surface concentration ($B_0$) was relatively large, but the difference was not significant. On the contrary, measured surface concentration, not calculated $B_0$, was $0.16 \pm 0.144$ and $0.11 \pm 0.072 \, \mu g \, L^{-1}$ in the downstream and upstream side, respectively. The downstream surface water had significantly higher chlorophyll a ($p < 0.05$).

DISCUSSION

The present study demonstrates the effects of various flow patterns in the vicinity of Komahashi No. 2 Seamount on phytoplankton concentrations in the overlying waters. The flow patterns we observed can be summarized as three different types: a homogeneous horizontal flow as defined above, a horizontal or vertical shear and a closed eddy. The flow condition is highly variable on a week-to-week and day-to-day basis as found during SE-89-7 and SE-89-8 cruises, and during SE-93-7 cruise, respectively. Under both the homogeneous and sheared flow conditions, we observed uplifted nutriclines (Figs. 3, 5 and 6).

Using the vertical distributions of temperature and salinity during SE-89-7 cruise, a height of Rossby’s depth was estimated to be 22 m at 500-m depth (Y. Sekine, personal communication), indicating that effects of current-topography interactions did not reach the euphotic zone. However, this is inconsistent with the observation of the elevated concentrations of nitrate at the base of the euphotic zone of about 60 to 80-m depths. The discrepancy may arise from the idealized assumptions in the calculation of the Rossby’s height, and from exceedingly complex patterns of stratified flow (RODEN, 1987). In addition, Komahashi No. 2 Seamount does not occur singly, but stands on Kyushu Palau Ridge. This topographic complexity makes it difficult to define the specific topographic effects of the seamount and its effects on current velocity fields in the study area. The distinct upliftings of nutricline aside the seamount (Figs. 3a and 6) seem to exemplify the difficulty. They can not be explained adequately in the present study whether they are directly associated with Komahashi No. 2 Seamount, or influence of neighboring water mass, such as Lee internal wave.

The anticyclonic eddy was found only in May 1990 out of ten-times observation. From the available hydrographic data, we cannot determine if the eddy was a manifestation of Taylor column. During this period the warm core eddy whose diameter was approximately 350 km existed in the southeast of the seamount (DEPARTMENT OF HYDROGRAPHY, 1990). Although such a warm core eddy was also developed in June 1991 and July 1992, an anticyclonic eddy was not found over the seamount. Thus, a direct relationship does not seem to exist between the formation of the eddy above the seamount and the warm core eddy in the east to southeast of the seamount. The closed eddy probably led to the highly elevated levels of subsurface chlorophyll a concentrations by entrapping of the closed water mass and preventing diffusion of the nutrients (BOEHLERT and GENIN, 1987; RODEN, 1987).
In spite of the elevation of the nutricline under both homogeneous and sheared flow conditions, the enhancement of chlorophyll \( a \) concentration occurred only in the homogeneous velocity field. It is likely that with vertical and horizontal shear, upwelled nutrients are dispersed by mixing with nutrient-depleted water too rapidly to allow phytoplankton biomass to increase. On the contrary, under the homogeneous flow condition, upwelled water masses are mixed at a lower rate and the elevated nutrients can be kept long enough to bring out the increase of chlorophyll \( a \). However, the upwelled nutrients are expected to raise overall phytoplankton productivity in the vicinity of the seamount even under the sheared flow condition. The inconsistency in literature on the effect of seamounts on lower food chain processes is probably ascribed in part to the large variability of the velocity field. Unfortunately few studies on the lower food chain processes around the seamount have provided data on velocity field. Consequently, their biological data were not necessarily interpreted sufficiently in relation with the velocity field. Since the effects of seamounts on the lower food chain processes are expected to have a variety of spatial and temporal scales, information on the velocity field is prerequisite for robust interpretation of the results.

The enhancement of chlorophyll \( a \) concentration was most apparent in the lower part of the euphotic zone. The uplifting of nutricline never reached the upper part of the euphotic zone and the 1-\( \mu \)M isoline of nitrate remained below the 5% light depth at most. Furthermore, no enhancement was found in the surface (Table 3). Thus, these observations lead to the conclusion that the primary effects of the seamount on phytoplankton production and biomass appear at the depth of subsurface chlorophyll maximum layer with only occasional effects near the surface (Table 2). For the latter cases, effects may thus be detectable by remote sensing of ocean color.

The downstream enhancement of phytoplankton abundance was more vital in the large forms including diatoms than pico- and nanoplanckters (FURUYA, in preparation). Although the subsurface chlorophyll maximum in the oligotrophic waters are dominated by pico- and nanoplankton (e.g., FURUYA and MARUMO, 1983; TAKAHASHI and HORI, 1984; LI and WOOD, 1988), micro- and mesoplanktonic diatoms occur ubiquitously even with low abundance (BEERS et al., 1975; GUILLARD and KILHAM, 1977; FURUYA and MARUMO, 1983). In spite of their low numerical abundance, they contribute significantly to total biomass under some conditions of episodic nutrient supply by utilizing the upwelled nutrients in precedence over small forms (GOLDMAN, 1988).

Horizontal scale of the area affected by the seamount was estimated using the integrated amount of chlorophyll \( a \) in the 30-m water column around the subsurface chlorophyll maximum (Table 3). First, stations that are affected by the seamount were chosen by chlorophyll amount above 7.6 mg m\(^{-2}\) (mean (10.7) minus one standard deviation (3.1)). Next, all the chosen stations were plotted on a chart with a boarder connecting outermost stations (Fig. 8). The resultant area is elongated east- and westward and the center of the area is in the western side of the seamount. This is because the homogeneous velocity fields had, in general, western components (Table 1). The area is approximately 100 km long and 50 km wide. Hence, the effects of the seamount have a horizontal scale of several tens kilometers. The subsurface
current velocity ranged from 15 to 75 cm s\(^{-1}\) atop the seamount. Therefore, the horizontal scale of the area corresponds to the time scales of 20 to 200 hours.

In conclusion, the topography-current interactions above Komahashi No. 2 Seamount induce perturbations in nutrients distributions, and enhance upward transport of nutrients into the bottom of the euphotic zone. Nutrient enrichment was occasionally accompanied by an elevated amount of chlorophyll \(a\) in the subsurface maximum layer of the seamount. The appearance of the high chlorophyll \(a\) patch seemed to depend on the velocity field of subsurface layers. Intense both vertical and horizontal shear activities in the velocity field may promote rapid diffusion of upwelled nutrients through mixing with surrounding nutrient-deplete waters. In this way, the effects of the upwelling can be obscured. However, even without obvious effects, the advected nutrient into the euphotic zone must raise new production and contribute to background biological activity in the lower euphotic zone. Since the population of seamounts is more than 30,000 in the Pacific Ocean (SMITH and JORDAN, 1988), and many of them are in the western Pacific, upward advection of nutrients into the euphotic zone over the seamounts is quite important in basin-scale carbon budget, especially in the new production.

**Acknowledgements**—We thank A. Kawamura, A. Tsuda and K. Takahashi for their cooperation at sea and Y. Sekine for discussion. The manuscript was improved by comments from J. Yoder and anonymous reviewers. Thanks are due to the captains, crew members and scientists of T/S Seisui Maru and R/V Tansei Maru cruises for their assistance. This study was supported by Grants (Nos. 03248106, 04232106, 04660204) from the Ministry of Education, Science and Culture of Japan.
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