Phytoplankton Growth Response to Wind Induced Regional Upwelling Occurring Around the Izu Islands off Japan

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Abstract: From frequent field observations performed in coastal waters around the Izu Islands, Japan, a clear regional upwelling associated with the wind was detected beside Nijima Island. Nutrient supply by the upwelling into the euphotic zone was confirmed, and the subsequent phytoplankton growth supported by the upwelled nutrients was evaluated. The upwelling and the nutrient supply occurred within a day over an area of ca. 400 km², and phytoplankton growth response occurred only a few days after the upwelling. Such regional upwelling is considered to be one of the major mechanisms supporting the high productivity of coastal waters.

1. Introduction

Phytoplankton production in the sea is primarily controlled by nutrient availability and solar radiation (Takahashi, 1980). Incoming solar radiation varies depending upon the sun’s altitude, the day length, and temporal cloud coverage. Both the sun’s altitude and the day length, which are affected by latitudinal and seasonal differences, change over large distances of more than 1,000 km and over long time scales of several months to several years. Cloud coverage may change over relatively short distances compared with the other two factors mentioned above, but will still lie in the mesoscale size range of more than 10 km. The time scale of cloud coverage is short varying over periods of minutes to a day. The generation time of phytoplankton is mostly one to a few days at the nonsexual reproduction stage, which could result in a time scale of a day to a few weeks for a noticeable change in phytoplankton biomass. The small size of individual phytoplankton of 0.5 to 1,000 μm allows formation of a variety of sizes of population distribution including minute patchiness.

Actual phytoplankton distribution in coastal waters, e.g., off the Pacific coast of the Japan Islands, varies over small distances of less than 10 km and short time scales of a few days (Takahashi et al., 1980). Such small and rapid changes are strongly associated with local changes in nutrient concentrations in the euphotic zone. This suggests that phytoplankton distribution in coastal waters is regulated primarily by nutrient availability rather than radiation conditions in the water. Therefore the key to understanding local changes observed in biological production processes in coastal waters lies in elucidation of the possible mechanisms of nutrient supply to the euphotic zone.

Nutrient supply to the euphotic zone occurs through both authochtonous and allochthonous processes. The former are supported by biological regeneration occurring in the euphotic zone, and are important for the maintenance of the level of existing production. The latter involve upwelling from the disphotic zone and horizontal water advection. In coastal regions, regional upwelling or intrusion is thought to be one of the major contributions to local fertilization of the ecosystem (Atkinson et al., 1978). Nutrient supply by upwelling and enhancing effects which upwelling has on biological production in the sea have been subjects of considerable attention (Walsh, 1975; Wroblewski and O’Brien, 1977; Yoder et al., 1984).

Several driving forces have been mentioned...
for the formation of regional upwelling: wind induced upwelling (Yoshida, 1955; Suginoohara, 1974) or upwelling due to the combined effects of ocean currents and topography (Fukazawa and Nagata, 1980), and oceanic eddies (Blanton et al., 1981). Kishi (1976, 1977) observed upwellings associated with the prevailing wind along the east coast of the Izu Peninsula, Japan. In the present study, an upwelling phenomenon due to the wind was observed around an island in the Izu island chain, and the associated increase of phytoplankton resulting from the nutrient enrichment by the upwelling was analyzed.

2. Materials and methods

Field observations were performed in the area around the Izu Islands (Fig. 1A). Sea surface temperature was determined daily at 13 shore stations, belonging to local regional fisheries laboratories, throughout the year. Wind record and other meteorological measurements were made at Iro-zaki Cape and Izu-Ohshima Island by the Japan Meteorological Agency.

Ship observations were made six times in total on the 16, 17 and 20 September 1980 by regional fisheries laboratories and ourselves at the stations shown in Figs. 1B and 2. Water temperature was determined with bathythermographs, and water samples were collected with buckets and Van Dorn type water bottles. Salinity, various nutrients, and chlorophyll a were analyzed according to the procedures described by Strickland and Parsons (1972). Phytoplankton cells preserved with neutralized formalin were counted by the technique of Utermöhl (1958).

3. Results

Figure 2 shows the day-to-day changes of surface water temperature around the Izu Islands between the 16 and 27 September. Temperature contours were drawn based on actual temperature measurements made daily at 13 shore stations at various geographical locations, and ship observations. Sea surface temperature in the entire area was also determined on 20 September using a radiothermometer from an aircraft flying 400 m above the sea surface. The flight path is shown in Fig. 2. On 16 and 17 September, sea surface temperature was over 24°C in the entire study area except for a slightly low water temperature below 24°C occurring along the east coast of the Izu Peninsula. On 18 September, a cold water mass with a temperature of less than 23°C appeared on the westside of Niijima Island, and it developed in size rapidly at the surface over the subsequent days. The initial surface area of the cold water mass observed on 18 September was about 400 km². Surface temperature determinations along the flight path of the aircraft clearly showed a cold water mass immediately to the west of Niijima Island, and the 23°C water extended towards

![Map of the study area. Black circles in (A) indicate the 13 shore stations belonging to regional fisheries laboratories at which surface temperatures were monitored, and white circles show meteorological observatories. Cruise tracks (front numbers) and occupied stations (back numbers) for the cruises on the 17 and 20 September are shown in (B).](image-url)
the Izu Peninsula. The surface water temperature around Nijima Island dropped to below 20°C and cold water covered the entire area around Nijima. The cold water area with a water temperature of <23°C reached a size of about 20,000 km² by 27 September and included four other neighbouring islands, and the strait between the islands and the Izu Peninsula was completely covered by the cold water. According to the Hydrography Service (1980), the cold water stayed in the area for almost one month until the middle of October.

Detailed observations were performed on 17 September in the strait between Nijima Island and the Izu Peninsula. Surface water temperatures were mostly over 24°C in the area except for low temperatures below 23.5°C which appeared around a peninsula off Shimoda (Fig. 3-1). High temperature surface waters over 25°C were mostly distributed in the southeastern half of the strait. Salinity was high on both sides of the strait; nearly 33.9% along the coast off Shimoda and over 34% at the center of the strait (Fig. 3-2). Based upon the temperature and salinity results, the surface water in the strait was tentatively classified into three different water masses; the northwest (NW), the central (CR) and the southeast (SE) waters, each of which was characterized by low temperatures and high salinities, intermediate temperatures and low salinities, and high temperatures and high salinities, respectively.

The NW water contained high concentrations of phosphate over 0.25 µM and nitrate plus nitrite over 1.0 µM and chlorophyll a around 0.5 µg l⁻¹ (Figs. 3-3, 3-4, 3-5 and 3-6). In the CR water, phosphate and nitrate plus nitrite concentrations were at intermediate levels, but silicate and chlorophyll a were high, reaching 7.59 µM and 1.5 µg l⁻¹, respectively. The SE water was characterized by low concentrations of <0.15 µM for phosphate, <0.5 µM for nitrate plus nitrite, <4 µM for silicate and <0.5 µg l⁻¹ for chlorophyll a.

On 20 September, three days after the previous ship observations, other detailed observations
were made along cruise tracks #3 and #4 (Fig. 1B). Two of the three water masses observed at different locations on 17 September were also identified on 20 September, although the geographical locations and the water characteristics were not always the same. The low salinity CR water of 17 September disappeared completely. The SE water of 20 September was characterized by low temperatures, high salinities and high concentrations of nutrients and chlorophyll a (Fig. 4) each of which reached 22°C, 34.26 ppt, 3.3 μM (NO₃⁻+NO₂⁻) and 3.1 μg chl a l⁻¹. In the NW water, nitrate plus nitrite was around 1 μM and chlorophyll increased a few times reaching nearly 3 μg l⁻¹, the temperature went up about 1°C, and the salinity was more or less at the same level.

Differences in each parameter between the 17 and 20 September were compared at the surface along cruise tracks #3 and #4 (Fig. 5). Temperature generally increased offshore with a slight drop at the most offshore stations on 17 September. Whereas there was a large temperature drop, particularly significant at a few offshore stations on 20 September. Temperature drops occurring at Station 13 on tracks #3 and #4 on 20 September were 2.30 and 2.84°C, respectively, compared to the previous values on 17 September. With the drop of temperature, salinity increased by 0.2 to 0.9 ppt over the entire
Fig. 5. Surface changes in temperature, salinity, nutrients and chlorophyll a along cruise tracks #3 and #4 on 17 and 20 September 1980. Numbers along the ordinate indicate stations: upper numbers are for 17 September and lower numbers for 20 September.

Fig. 6. Vertical profiles of water temperature along cruise tracks #3 and #4 on 17 and 20 September 1980.

area except for a few nearshore stations and was mostly over 34% on 20 September.

Large changes in the nutrients and chlorophyll distribution also occurred between 17 and 20 September associated with the physical changes mentioned above. The concentrations of nitrate plus nitrite decreased almost exponentially with distance offshore on 17 September with a few small increases in concentration along the cruise tracks. On 20 September, on the other hand, high concentrations of nitrate plus nitrite were detected at a few offshore stations. The increase of nitrate plus nitrite between these two days at Station 13 was over 3 μM. A similar general trend to that of nitrate plus nitrite was also observed in the distribution of phosphate. Silicate showed a complicated pattern compared with the other two nutrients, although the general trend was the same.

Changes in environmental conditions between 17 and 20 September, were further evaluated in the water column from vertical profiles of water temperature (Fig. 6). On 17 September, there was a warm water in the center of the strait, and there was a slightly colder water on both sides of the strait. A weak frontal structure was observed between the water masses at Station 5 along cruise tracks #3 and #4, and at Station 13 along cruise track #4. On 20 September, the same general features were main-
Table 1. Dominant phytoplankton (cells ml\(^{-1}\)) at several stations on 17 and 20 September 1980.

<table>
<thead>
<tr>
<th>Track-Station</th>
<th>17 September 1980</th>
<th>20 September 1980</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>1-6</td>
<td>3-13</td>
</tr>
<tr>
<td>Nitzschia spp.</td>
<td>15.8</td>
<td>61.9</td>
</tr>
<tr>
<td>Tabellaria sp.</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Asterionella sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chaetoceros spp.</td>
<td>26.4</td>
<td>38.9</td>
</tr>
<tr>
<td>Rhizosolenia spp.</td>
<td>4.9</td>
<td>5.1</td>
</tr>
<tr>
<td>Leptocylindrus sp.</td>
<td>9.9</td>
<td>16.1</td>
</tr>
<tr>
<td>Bacteriostrum spp.</td>
<td>2.3</td>
<td>9.9</td>
</tr>
<tr>
<td>Coscinodiscus sp.</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Eucampia sp.</td>
<td>3.7</td>
<td>6.0</td>
</tr>
<tr>
<td>Skeletonema sp.</td>
<td>4.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Thalassiosira sp.</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Biddulphia sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemialulus sp.</td>
<td>0.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Corethron sp.</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Ditylum sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peridinium spp.</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Ceratium sp.</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Prorocentrum sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dinophysis sp.</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Oscillatoria sp.</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Dominated, but the frontal structure on the southeastern side of the strait was much more pronounced. A strong upwelling feature was clearly detected along both tracks #3 and #4. The upwelling area along #3 was broad reaching 10 km and that of #4 was narrow but had steep vertical gradients in the environmental parameters.

Dominant phytoplankters in the area were diatoms (Table 1). On 17 September, centric diatom species, Chaetoceros spp., were the most abundant in all the samples examined except for Station 7 on cruise track #5, where pennate diatoms, Nitzschia spp., were abundant. On 20 September, pennate diatoms took over dominancy in all samples examined.

4. Discussion

Daily changes of sea surface temperature showed that a cold water mass appeared on the western side of Niijima Island on 18 September, developed in surface area over the following days and formed a rather stable condition which was maintained for one month (Fig. 2; Hydrography Service, 1980). Ship observations performed on 17 and 20 September showed that there was an indication of upwelling of subsurface water in the vertical profiles of temperature along cruise tracks #3 and #4. The area of possible active upwelling, evaluated from vertical temperature profiles, was small in spatial size, and was characterized by strong uplift of low temperature water (Fig. 6). Associated with the lowering of the surface temperature, the concentrations of various chemical parameters increased greatly: salinity reached 34.26%, nitrate plus nitrite 3.4 μM, and phosphate 0.35 μM. A question is "what was the major driving force for the formation of the upwelling observed?" According to a report by the Hydrography Service (1980), south of 34°N the Kuroshio was flowing towards the east but changed in direction towards the northeast off the east of the Izu Islands. Surface currents measured in the study area indicated that there was no consistent strong current at least until 20 September, 1980 (Hydrography Service, 1980). This indicates that there was no major ocean current around the west side of Niijima and neighbouring islands during the study period.
Figure 7 shows the wind direction and speed determined at Iro-zaki Cape and Izu-Ohshima Island every 12 hr between 15 and 20 September. Weak westerly or southeasterly winds were blowing at 2100 on 17 September, but the wind changed direction to the northeast by 0900 on 18 September. The northeast wind continued until at least 0900 on 20 September. The speed of the NE wind was in the range of 5–12 m sec$^{-1}$. The possible surface current induced by the NE wind is shown by arrows in Fig. 7. On 18 September the change of wind direction from southwest to northeast initially caused a wind induced surface current along the wind direction (i.e., towards SW). After that the current direction changed to the Ekman transport direction (i.e., towards NW) within inertial time. This northwestern current is considered to have developed a divergence of surface water off the west coast of Niijima, and a cold upwelled water mass appeared around Niijima (indicated by shaded area in Fig. 7). In the vicinity of a straight coast the upwelled region propagates along the coast as coastal-trapped waves (Suginoohara, 1982), but when there is no strait coast, the upwelled cold water tends to stagnate as in the present situation (Kishi and Suginoohara, 1974). The stagnant cold water occurring around the islands (Fig. 2) could form a geostrophically balanced cyclonic eddy that persisted until at least 27 September with the help of spin-up by a branch of the Kuroshio.

A sharp upward lifting of low temperature water at Station 14 along cruise track #4 on 20 September indicated the presence of newly upwelled water. Nutrient concentrations were all high, for example, 3.34 μM for nitrate plus nitrite and 0.34 μM for phosphate, but chlorophyll $a$ concentration was only 0.88 μg l$^{-1}$ at the surface at Station 14 along cruise track #4. In the upwelled water along cruise track #3, on the other hand, chlorophyll concentrations as well as nutrient concentrations were high; 3.1 μg l$^{-1}$ of chlorophyll $a$ and 3.0 μM of nitrate plus nitrite at Station 13. This suggests that the upwelled water along track #3 had been present for sometime since it came to on/near the surface, allowing chlorophyll to build up to a certain level while nutrients still remained in the water. This interpretation is further supported by the weak lifting of low temperature water suggested by the pattern of the vertical profiles of temperature and the wide expansion of the cold water.
Ishizaka et al. (1983) found that chlorophyll increased almost logarithmically once subsurface water is upwelled to the surface in the present study area, and that the specific growth rate of phytoplankton depends on the surrounding water temperature and the ambient nutrient concentrations. A value of 1.64 μg chl a/(μg atom N) was obtained for the ratio of (chlorophyll)/(organic nitrogen) in the present study area (Ishizaka et al., 1983). Assuming that the initial chlorophyll concentration was 0.5 μg l⁻¹, i.e., the chlorophyll concentration of the subsurface water in the area before upwelling, the chlorophyll a increase was 2.6 and 0.3 μg l⁻¹ at Stations 13 (#3) and 14 (#4), respectively, which corresponds to 1.6 and 0.2 μM of nitrate plus nitrite based upon the relation mentioned above. By adding the nutrient concentration estimated to the observed nutrient values, possible initial concentrations of nitrate plus nitrite of 4.6 and 3.6 μM for Stations 13 (#3) and 14 (#4), respectively, were obtained. The specific growth rate of phytoplankton consisting of diatoms, estimated from Ishizaka et al.'s results, is 0.8 day⁻¹ for the present initial nutrient concentrations and temperature of 22°C. If we assume that the phytoplankton increase follows the logarithmic relation:

\[ C_2 = C_1 \exp(\mu(t_2 - t_1)) \]

where \( C_1 \) and \( C_2 \) are phytoplankton biomass, chlorophyll a in this case, at time \( t_1 \) and \( t_2 \), respectively, and \( \mu \) is the specific growth rate. By using the relations of the specific growth rate and various initial conditions mentioned above, the time required to reach the observed chlorophyll levels on 20 September at Stations 13 (#3) and 14 (#4) were estimated. It was estimated that 2.3 and 0.6 days were required at Stations 13 (#3) and 14 (#4), respectively. This estimate gives strong support to the view that the observed high concentration of chlorophyll a was produced after 17 September when the water was upwelled.

In conclusion, a regional upwelling associated with the wind was detected around an island in coastal waters around the Izu Islands. Associated with the upwelling, large amounts of nutrients appeared in the upwelled water, which resulted in a subsequent phytoplankton bloom. The time scale for nutrient supply to the euphotic zone by the upwelling was expected to be within a day or so. The areal size of the upwelling at the surface was initially similar in size to that of the island (~400 km²), and subsequently developed to a larger scale of 20,000 km² within ten days. Phytoplankton growth using the upwelled nutrients occurred instantaneously and a phytoplankton bloom consisting mainly of centric diatoms was formed in the upwelled water within a few days after upwelling. These results suggest that phytoplankton production in coastal waters is strongly enhanced by temporal regional upwellings. It is expected that such upwellings occur frequently in the area due to the combined effects of current action associated with the wind, ocean currents, and coastal topography. Such upwellings are probably one of the major mechanisms supporting the high productivity observed in this coastal area. The quick responses of the phytoplankton to the supply of nutrients in the coastal water also supports the view that nutrient supply occurs frequently in the area. Put another way, phytoplankton which can respond quickly to temporal nutrient supply can become dominant in coastal waters in which there are frequent upwellings.

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References

Regional Upwelling and Phytoplankton


伊豆諸島周辺に発生した風による局地性漬昇中での植物プランクトンの増殖応答

高橋 正 征*, 岸 道 郎**

要旨：伊豆諸島周辺の沿岸海域で発生した頻繁な海洋観測により、島の周辺に風によってできたと思わせる明瞭な局地性漬昇を検出した。漬昇による有光層への栄養塩供給が確認され、それに因ついて漬出栄養塩を使用した植物プランクトンの増殖が観察された。漬昇により栄養塩供給は約 400 km²、1 日程度の増殖面積で観察され、植物プランクトンの増殖応答は漬昇発生後数日で認められた。こうした局地性漬昇は沿岸域の高い生物生産を支える重要な機構のひとつであると考えられるに至った。

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