Characteristics of primary production in a eutrophicated bay

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Abstract The primary production of phytoplanktons provides organic matter in high concentration in eutrophicated Hakata bay in Japan, even during the winter season in spite of low water temperature. Phytoplanktons may have the biological capabilities to maintain activities of photosynthesis under unfavorable conditions, and these capabilities affect water quality in the bays. In this study, characteristics of primary production were analyzed with a simple box-type ecosystem model. We introduced a concept of efficiency for absorption of sunlight energy to our simulation model of water quality to explain rather high growth rates of phytoplanktons in low sunlight intensity. Through simulation with a box model, we found that the efficiency of primary production in winter is higher than that in summer. It was suggested that the organic pollution comes from dissolved organic carbon (DOC) throughout the year and that the DOC is originated from the primary production of phytoplanktons in biological response of the seasonal change of ambient conditions.

Keywords Enzyme; light intensity; nutrient; photosynthesis; phytoplankton; primary production

Introduction

Hakata Bay, a semi-closed and eutrophicated bay located in western Japan, has a population of about 1,900,000 in its catchment area (refer to Figure 1). Organic carbon in the bay remains stable in concentration throughout the year, at high levels in the winter season. Nakanishi *et al.* (1975) reported that organic pollution in a eutrophicated bay is caused by a high production rate of marine-derived organic matter such as phytoplanktons. A high level of organic carbon in winter is considered to result from the growth of phytoplanktons and also abundant nutrients loaded from the catchment area encourage phytoplankton activity. Although plenty of research has been done on water quality management and prevention of eutrophication in Hakata bay (Uchida *et al.*, 1994; Fujita *et al.*, 1999), the mechanism of organic pollution during the winter season in the bay has not been investigated yet. Therefore, we tried to explain, with a box model, the process of primary production that arises easily even under unfavorable conditions. The objectives of this study are to apply the efficiency of photosynthesis on light intensity and on intake of nutrients to the model and to understand the potential changes of primary production in this eutrophicated bay.

Methods

Description of study area

Field observations. The study area is the eastern part of Hakata bay, the area surrounded by the thick broken line as shown in Figure 1, and is 34.9 km^2 in area, 197.8 $\times 10^6$ m^3 in volume, and 5.6 m in average depth. In the bay, phytoplanktons, nutrients such as NH_4 (ammonium), NO_3 (nitrate), and PO_4 (phosphate), and DON (Dissolved Organic Nitrogen), DOP (Dissolved Organic Phosphorus), DOC (Dissolved Organic Carbon), POC (Particulate

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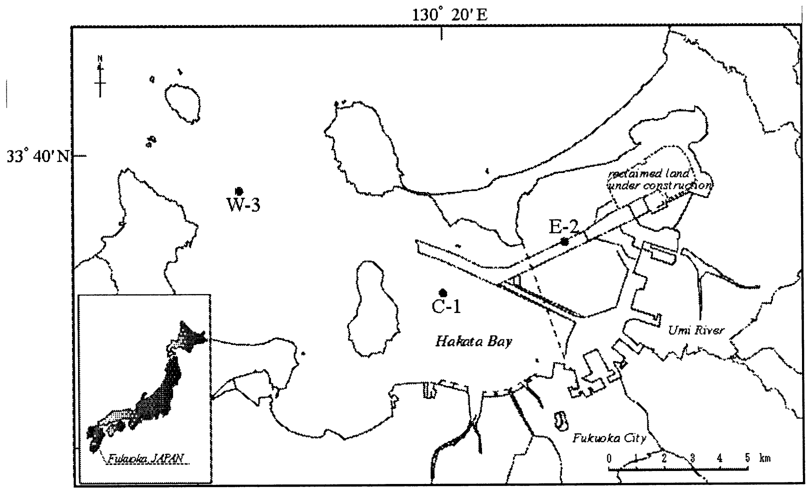

Figure 1 Study area

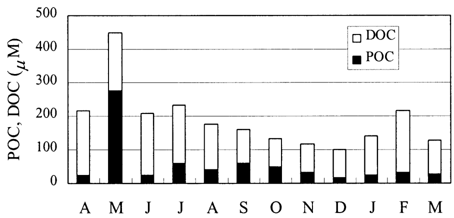

Figure 2 Seasonal variations in organic carbon (DOC, POC) at the surface of the sea (Stn. E-2)

Figure 3 Seasonal variations in population of phytoplanktons at the surface of the sea (Stn. E-2)

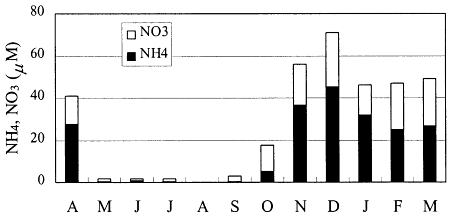

Figure 4 Seasonal variations in NH_4, NO_3 at the surface of the sea (Stn. E-2)

Organic Carbon), and Chlorophyll-*a* were monitored at three stations from April 1996 to March 1997 by the Port and Harbor Bureau of Fukuoka (Fukuoka City, 1997). The monitoring was carried out at the stations, W-3, C-1, and E-2, at the surface (0.5 m) of the sea, middle layer (2.5 m), and bottom layer (1m above the seabed). During the period, several observations on loading from the land were carried out at the Umi River flowing into this bay (refer to Figure 1).

Seasonal variation of water quality. Figures 2, 3, and 4 show variations of organic carbon such as DOC and POC, phytoplankton population, nutrients such as NH_4 and NO_3 in this bay. The variation of DOC is not large and its concentration is at a high level even in winter. Phytoplanktons observed are *Dinoflagellates* in spring and Diatoms in the other seasons. *Diatoms*, dominant species of this bay, appear after the rainy season June and July. Most of NH_4 and NO_3 is consumed for primary production and other reactions from May to September. On the other hand, much nutrient remains in the winter season. In general, it is

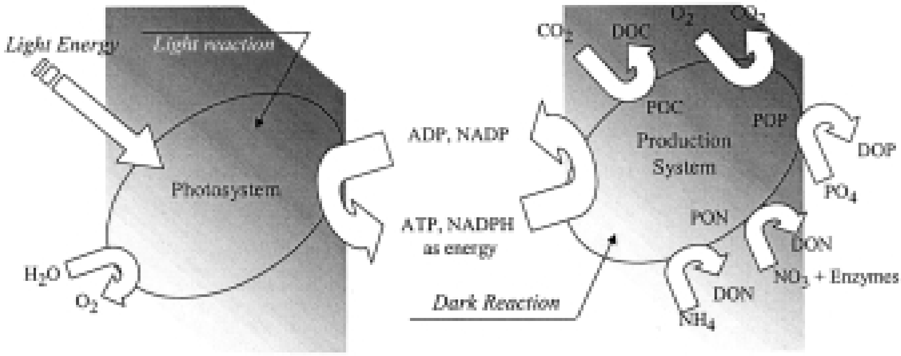

Figure 5 System of photosynthesis

considered that the growth rate of phytoplanktons is mainly controlled by water temperature and sunlight intensity. However, the populations of phytoplanktons in this bay are also high even in the winter season with low water temperature and sunlight intensity. This fact suggests that the growth of phytoplanktons might be affected by other factors in winter. Our assumption is based on the idea that it would occur at high efficiency of nutrient intake and absorption of sunlight energy in winter compared with that of summer, irrespective of low water temperatures. Because a large amount of nitrogen exists in the winter season.

Modeling concept and structure

We simulated seasonal variations of phytoplankton populations, Chlorophyll-*a*, NH_4, NO_3, PO_4, DOC, DON, and DOP with the data observed from April 1996 to March 1997 at Stn. E-2 in the study area after constructing a box model with the concept described below.

Mechanism of light energy use in photosynthesis. Photosynthesis in phytoplanktons consists of two reactions called light and dark reactions (refer to Figure 5). The former are to produce energy such as ATP (*adenosine 5'-triphosphate*) and NADPH (*nicotinamide-adenine dinucleotide phosphate*) for biochemical reaction (reduction) by converting light energy in photosystems. The latter are to produce organic matter for phytoplankton growth by reduction in carbon dioxide (CO_2) using the energy of ATP and NADPH provided from the light reaction (Conn *et al.*, 1965). Nutrients such as N and P are also essential for phytoplankton to grow. They also require the energy with ATP and NADPH for producing organic matter as well as reducing CO_2. These biochemical reactions, converting inorganic matter into organic matter, are carried out by some enzymes, which are also produced by using light energy. In other words, when the efficiency of biological absorption of light energy is high in spite of low sunlight intensity such as in the winter season, then a large amount of primary production is predictable.

Form of nitrogen in intake. Phytoplanktons take nitrogen in the form of both ammonium (NH_4) and nitrate (NO_3) from water during the dark reaction in photosynthesis. In the case that intake of nutrients takes place with the form of NO_3, phytoplanktons must produce extra enzymes, which are *nitrite-reductase* and *nitrate-reductase*, to reduce NO_3 to NH_4 by way of the formation of NO_2 because the composition of protein requires the formation of NH_4 for amino acids bonding. On the contrary, they do not need these enzymes in case of NH_4 because they can use it directly for biological composition. That is, the form of NH_4 on intake of nitrogen is more favorable in photosynthesis than that of NO_3 based on the absorption efficiency of light energy for biochemical reactions (refer to Figure 5). Moreover, concerning the reciprocal relation between NO_3 and NH_4, it is well known that the existence of

NH_4 inhibits intake of NO_3 under the dark reaction (Zevenboom *et al.*, 1981). The inhibition of intake F is formulated as follows:

$$F = 1 / (1 + S_{NH4} / K_i) \quad (1)$$

where K_i is the inhibition coefficient, and S_{NH4} is the concentration of NH_4.

The ammonium intake is said to be not affected by nitrate (Nakamura, 1985).

Formulation and assumptions

Absorption efficiency of light energy. We, therefore, assumed that the inhibition of intake of NO_3 by NH_4 helps the absorption of light energy because phytoplanktons do not need to produce some enzymes for reduction in NO_3. That is, the higher the inhibition for NO_3 is, the higher the absorption efficiency of light energy is. Accordingly, the absorption efficiency of light energy (ε) is given as a function of the value F as follows:

$$\varepsilon = \alpha_1 \exp(1 - \beta_1 F) \quad (2)$$

where F is the inhibition factor for intake of NO_3 by NH_4, and α_1 and β_1 are constants.

Growth rate of phytoplanktons. The growth rate of phytoplankton depends on the ambient conditions such as water temperature, light intensity, concentration of nutrient, and absorption efficiency of light energy. The changes in population of phytoplanktons and the final growth rate (μ_e) are given as a function of these factors as follows:

$$\partial P/\partial t = B1 - B2 - B3 - B4$$

$$B1 = P (\mu_e - \mu')$$

$$B2 = \alpha_2 B1 \exp(\beta_2 T)$$

$$B3 = \alpha_3 B1 \exp(\beta_3 T)$$

$$\mu_e = \mu (S) f(T) f(I) \varepsilon$$

$$\mu (S) = \min(\mu_N, \mu_P)$$

$$\mu_N = \mu_N{}^* (1 - q_0^N/Q_N)$$

$$Q_N' = q_0^N (Q_N'$$

$$Q_N' = Q'_{NH4} + Q'_{NO3}$$

$$Q_N'{}_{H4} = V_{max}^{NH4} S_{NH4} / (K_S^{NH4} + S_{NH4})$$

$$Q_N' O_3 = F V_{max}^{NO3} S_{NO3} / (K_S^{NO3} + S_{NO3})$$

$$\mu_P = \mu_P{}^* (1 - q_0^P/Q_P)$$

$$Q_P = q_0^P (Q_P'$$

$$Q_P' = Q'_{PO4} = V_{max}^{PO4} S_{PO4} / (K_S^{PO4} + S_{PO4})$$

$$f(T) = \{ T / T_{opt} \exp(1 - T / T_{opt}) \}^m$$

$$f(I) = (I / I_{opt} \exp(1 - I / I_{opt}) \}^n$$

$$I = I_0 \exp(- k Z) \quad (3)$$

where P is the total population of phytoplanktons, $B1$ is the growth of phytoplanktons, $B2$ is the grazing by zooplanktons, $B3$ is the the mortality of phytoplanktons, $B4$ is advection, μ´

is the respiration rate of phytoplanktons under the dark reaction, α_2, α_3, β_2, and β_3 are the constants for the function of water temperature, and $\mu(S)$ is the growth rate decided by interdependence among nutrients, $f(T)$ is the function depending on water temperature, $f(I)$ is the function depending on light intensity, $\mu^*_{N,P}$ is the growth rate at infinite $Q_{N,P}$, $q_0^{N,P}$ is the minimum cell quota of nutrient, $V_{max}^{NH4,NO3,PO4}$ is the maximum intake rate of nutrient, $S_{NH4,NO3,PO4}$ is the concentration of ambient nutrients, $K_S^{NH4,NO3,PO4}$ is the half saturation coefficient of nutrient, T_{opt}, I_{opt} is the optimum water temperature and light intensity, m, n, and k are constants, and Z is the depth at measurement.

We carried out simulation every quarter of a day ($\Delta t = 0.25$) for a year around.

Results and discussion

Seasonal variation of phytoplankton population

We simulated yearly growth of phytoplanktons with a box model corrected with the coefficient for absorption efficiency of light intensity (ε), which is a function of inhibition for intake of nitrates. The result as shown in Figure 6 shows good agreement with the observed data. Moreover, we calculated the concentration of Chlorophyll-*a* converted with the ratio of Chlorophyll-*a* / *P* (population of phytoplanktons) based on the observed data (refer to Figure 7). The population of phytoplanktons calculated ranges from about 0 to 8×10^6 cells $\cdot$ L^{-1}, and the largest population is seen in the spring season. It is nearly nought in population in June and August and it must be caused from the lack of nutrients consumed immediately for the primary production, especially nitrogen defects from high denitrification activity at such high water temperature. In winter a level of 2×10^6 cells $\cdot$ L^{-1} in phytoplankton population, the almost the same as in summer or a third of peak numbers in spring, exists even though low water temperature is calculated. Besides, the concentration of Chlorophyll-*a* tends to be lower than the observed data from July to September. This discrepancy must result from using the ratio in conversion of population to Chlorophyll-*a* concentration. The levels of primary production in summer and winter seem to be almost the same in spite of the fact that ambient water bodies are very different in character.

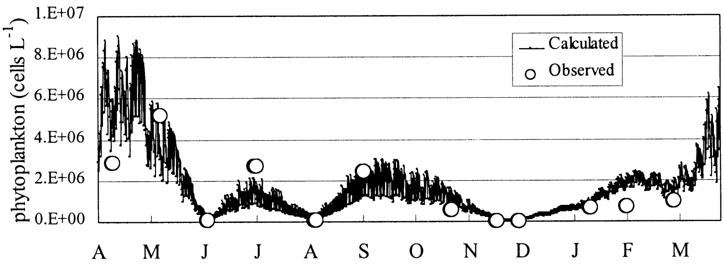

Figure 6 Seasonal variations in population of phytoplanktons

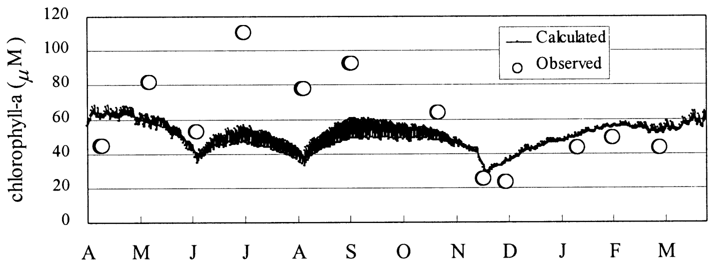

Figure 7 Seasonal variations in Chlorophyll-*a*

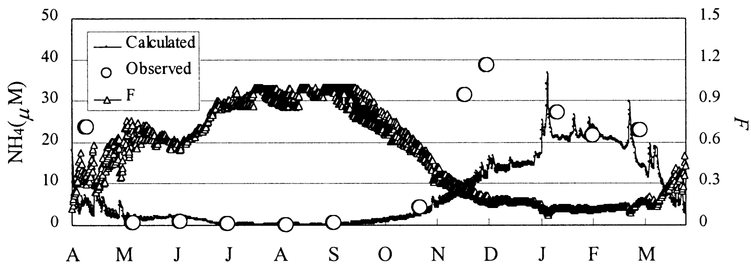

Figure 8 Seasonal variations in NH_4

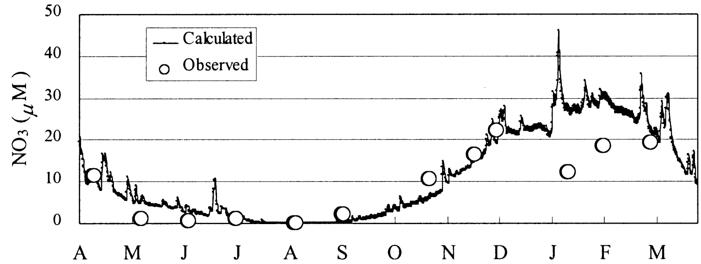

Figure 9 Seasonal variations in NO_3

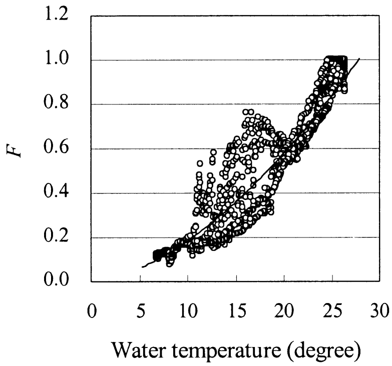

Figure 10 Relationship between *F* values and water temperature

Inhibition of ammonium for nitrate intake

The inhibition of intake of NO_3 by NH_4 (*F*) is seen in Figure 8. The value *F* decreases from autumn to winter, because much extra NH_4 is allowed to exist by the decrease in nitrification with low water temperatures. Although *F* keeps a high level in summer in spite of the release of NH_4 from the sea bottom with deficiency of oxygen, the increasing nitrification and denitrification might have increased more (refer to Figures 8 and 9). It is clear that the value *F* responds well to the change of water temperature as shown in Figure 10.

Efficiency of absorption of light energy in primary production

We formulated the absorption efficiency of light energy for photosynthesis in Eq. (2) and applied it to our model. The result is represented in Figure 11 with the function depending on water temperature $f(T)$ and that of light intensity $f(I)$, and ε based on *F*. The value ε is functioned to have a peak at February, the lowest water temperature month in the year. As a result, the final growth rate (μ_e) is flattened through the year according to Eq. (3). This makes the capability of growth of phytoplanktons higher in the winter season as shown in Figure 4.

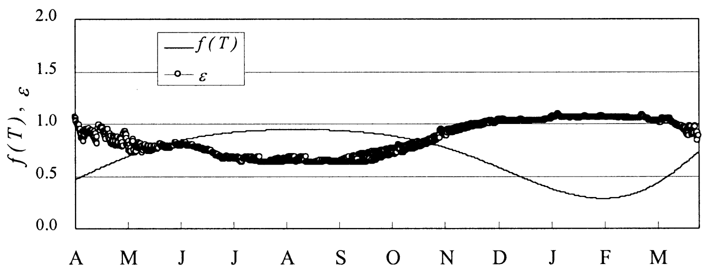

Figure 11(a) Seasonal variations in *f(T)* and ε

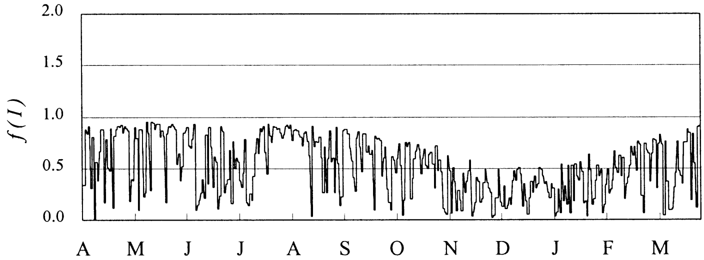

Figure 11(b) Seasonal variations in *f(I)*

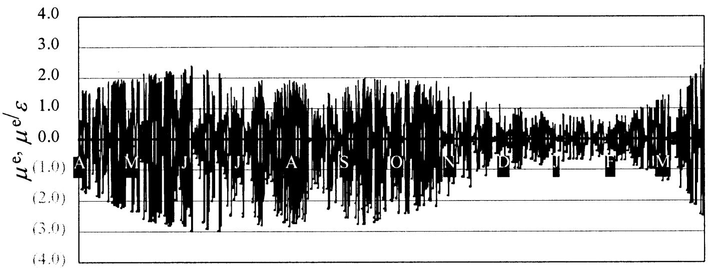

Figure 11(c) Seasonal variations in μ_e, μ_e/ε

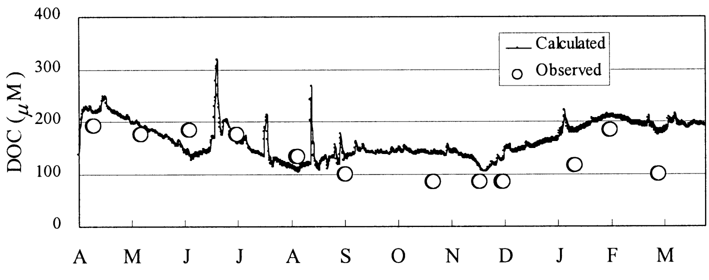

Figure 12 Seasonal variations in DOC

Potential of primary production

The concentration of DOC usually keeps stable irrespective of the change in water temperature (refer to Figure 12). We thought that this stability comes from the exudation of phytoplankton, whose DOC is difficult to be decomposed because of high-density molecules. We identified two factors to understand: the potential of primary production (δ) and efficiency

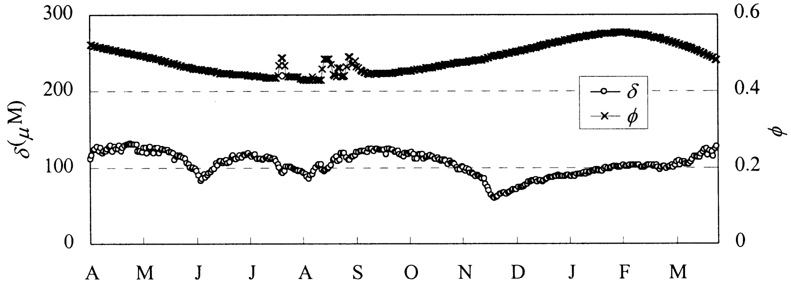

Figure 13 Seasonal variations in values of δ and φ

of primary production (φ), which are represented on the basis of carbon concentration as follows:

$$\delta\,(\mu M) = (Primary\ production) + (Exudation) + (Grazing) + (Mortality) + (Advection)$$

$$\phi = S_{Chla}/\delta \qquad (4)$$

where S_{Chla} is the calculated concentration of Chlorophyll-*a*.

Consequently, we understood that the value of φ in the winter season is a little higher than the other seasons except a short period in summer. The fact of high φ in summer is considered to be caused from decreased inhibition of NO_3 by NH_4 due to the high activity of nitrification in this term. The value of (tends to be high corresponding to increasing of the water temperature (refer to Figure 13).

Conclusions

Characteristics of primary production

It was found through this simulation with a simple box-typed model that the growth rate of phytoplanktons in the primary production is controlled by the absorption efficiency of light energy as well as water temperature, light intensity, and ambient concentration of nutrients. The absorption efficiency of light energy is described as a function of the inhibition coefficient (*F*) in nitrogen intake and water temperature. Moreover, the winter season shows the higher efficiency of primary production (φ) because phytoplanktons can use less energy advantageously under unfavorable conditions. As it turned out, the high potential of primary production value (δ) is associated with low φ value in high water temperature and sunlight intensity in summer, and low δ value with high φ value in low water temperature. Consequently, it is concluded that high concentrations of organic matter in winter consist mainly of DOC originating from primary production, supported by the adaptability of phytoplanktons for ambient conditions. And these characteristics of primary production keep the concentration of DOC in this bay stable throughout the year.

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