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Relationship between Chlorophyll *a* Concentration at the Sea Surface and Standing Stock of Chlorophyll *a* in the Euphotic Layer in the Seto Inland Sea, Japan.

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Abstract The relationship between chlorophyll *a* concentration at the sea surface and standing stock of chlorophyll *a* in the euphotic layer in the Seto Inland Sea was investigated in order to estimate the primary production from the data of chlorophyll *a* concentration at the sea surface obtained from the ocean color image by a satellite. We may reasonably conclude that the standing stock of chlorophyll *a* in the euphotic layer and primary production can be estimated from the chlorophyll *a* concentration at the sea surface in the Seto Inland Sea.

Key words: primary production, chlorophyll *a*, euphotic layer, satellite image

1. INTRODUCTION

The Seto Inland Sea is a semi-enclosed coastal sea in Japan and is well known as a treasury of fishery stocks due to the variety of fish species and their abundance. It is important for the management of fish stocks to understand the characteristic of primary production because the primary production is the first step in marine food chain. In the Seto Inland Sea, several measurements of the primary production by means of field experiments have been made (e. g. ENDO, 1970; ENDO and OKAICHI, 1977; YAMAGUCHI and ANRAKU, 1984; UYE *et al*, 1987). These measurements have been carried out using *in situ* incubation methods. Therefore, these measurements are limited both temporally and spatially. In order to solve these difficulties of field measurements, the primary production have been estimated from the standing stock of chlorophyll *a* (chl.*a*) in the euphotic layer and the mean ratio of primary production to chl.*a* standing stock in the euphotic layer (UYE *et al.*, 1987; HASHIMOTO *et al.*, 1997a; TADA *et al.*, 1998).

Recently, the observations of the chl.*a* concentration at the sea surface by the ocean color image from the satellite have been successfully carried out (SMITH *et al.*, 1982; SAINO, 1993; KAWAMURA *et al.*, 1998). It is necessary for the estimation of the primary production using the ocean color image to make clear the relationship between chl.*a* concentration at the sea surface and the standing stock of chl.*a* in the euphotic layer.

KASAI *et al.* (1998) examined in detail the relationship between chl.*a* concentration at the sea

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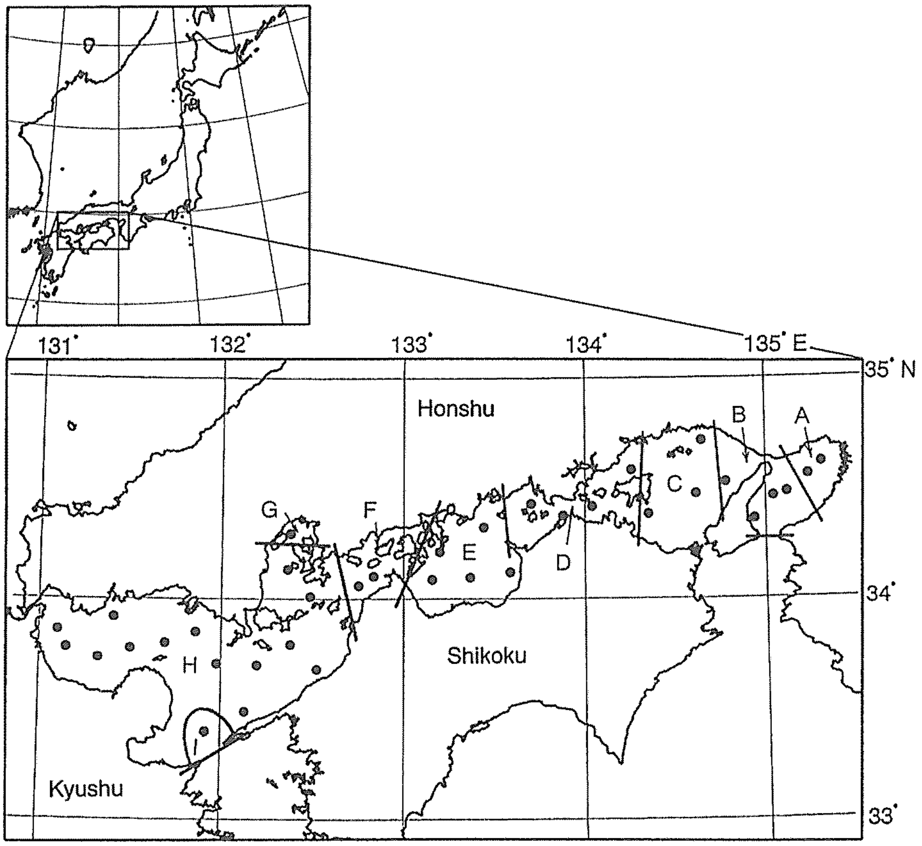

Fig. 1. Location of sampling stations and areal zonation in the Seto Inland Sea.

surface and the standing stock of chl.*a* in the euphotic layer in the Oyashio region, the western subarctic Pacific. In the Seto Inland Sea, the complexities of oceanographic condition and primary production system are much larger than those in the open ocean like the Oyashio region due to complicated coastal geometries and supply of materials from land. Therefore, the geographical differences of the primary production scheme in the Seto Inland Sea are very large. Then, it will be important to analyse the oceanography data every sub-area for the estimation of the primary production using the ocean color image from the satellite in the Seto Inland Sea. We divide the Seto Inland Sea into nine sub-areas according to characteristic of the seasonal variation in the vertical mixing condition (Fig. 1; HASHIMOTO *et al.*, 1997a).

In the present study, we examine the relationship between chl.*a* concentration at the sea surface and the standing stock of chl.*a* in the euphotic layer in each sub-area of the Seto Inland Sea. Moreover, we discuss the possibility of the estimation of the primary production from the chl.*a* concentration at the sea surface in the Seto Inland Sea.

2. OBSERVATIONS

Oceanographic observations were made at 37 stations throughout the Seto Inland Sea by T. R. V. Toyoshio-Maru of Hiroshima-University during four seasons; Autumn: 12-22 October 1993, Winter: 8-21 January 1994, Spring: 12-22 April 1994 and Summer: 20-30 June 1994 (Fig. 1:

HASHIMOTO *et al.*, 1997b). At all stations, Secchi disk depth and vertical profile of *in vivo* chlorophyll fluorescence were measured with CTD system (SBE 9/11 plus, Sea Bird Electronics Inc.; Fluorometer, Sea Tech Inc.). In addition, at all stations sea surface water was collected. Water sample for chl.a was immediately filtered through a precombusted Whatman GF/F fiter (450°C, 2h) and was preserved in N,N-dimethylformamide until analysis at -20°C (SUZUKI and ISHIMARU, 1990). Chl.a concentration was determined by Lorenzen's (1967) spectrophotometric method (PARSONS *et al.*, 1984). *In vivo* chlorophyll fluorescence values from CTD system were calibrated with extarcted chl.a values. Euphotic layer depth (h) is estimated as 2.8 times Secchi disk depth, according to HASHIMOTO and TADA (1997).

3. ANALYSIS

The ocean color measured by a remote sensing depends on the standing stock of chl.a from the sea surface (0m depth) to one optical depth, which is the reciprocal of the attenuation coefficient (SMITH, 1981; SMITH and BAKER, 1978). In this study, chl.a concentrations at the sea surface (Cs) are calculated as the mean concentration of chl.a concentrations within one optical depth. The attenuation coefficient (k ; m^{-1}) is estimated as $1.6/D_{SD}$ (HASHIMOTO and TADA, 1997), D_{SD} is Secchi disk depth.

The relationship between Cs and standing stock of chlorophyll a in the euphotic layer is defined as follows.

Assuming that the vertical profiles of chl.a in each sub-area have similar shapes, the mean concentration of chl.a in the euphotic layer (Ce) is estimated by

$$\mathrm{Ce} = \alpha \times \mathrm{Cs}, \qquad (1)$$

where α is a proportion constant in each sub-area. The attenuation coefficient (k) is divided into the attenuation due to the phytoplankton and the others (Seawater, detritus and so on)(LORENZEN, 1972; SMITH and BAKER, 1978; MOREL, 1988),

$$\mathrm{k} = \mathrm{kc} \times \mathrm{Ce} + \mathrm{kx} \qquad (2)$$

where kc ($m^2\ mg^{-1}$) is specific attenuation coefficient by chl.a and kx is the attenuation coefficient independent of chl.a. Assuming that h is propotinal to the reciprocal of k (KASAI *et al.*, 1998), the euphotic layer depth (h) is expressed by the following equation,

$$\mathrm{h} = \frac{\beta}{\mathrm{kc} \times \mathrm{Ce} + \mathrm{kx}} \qquad (3)$$

where β is a proportion constant between the optical depth and the euphotic depth. From equations (1) to (3), the standing stock of chl.a in the euphotic layer (Se, mg m^{-2}) can be expressed as follows,

$$\mathrm{Se} = \mathrm{h} \times \mathrm{Ce}$$

$$= \alpha \times Cs \times \frac{\beta}{kc \times \alpha \times Cs + kx}$$

$$= C1 \times \frac{Cs}{Cs + C2} \qquad (4)$$

$$C1 = \beta / kc, \; C2 = kx / (\alpha \times kc).$$

Thus, Se is expressed as a rectangular hyperbola formula for Cs (KASAI *et al.*, 1998). The equations (1) and (3) shows that h becomes small as Cs becomes high due to the self-shielding effect by the phytoplankton. Therefore, Se can not become large endlessly and approaches an asymptotic value gradually as Cs becomes high.

4. RESULTS AND DISCUSSION

The factors C1 and C2 in Eq. (4) for each sub-area are estimated using the least square method (Fig. 2). The factors C1 and C2 were listed in Table 1.

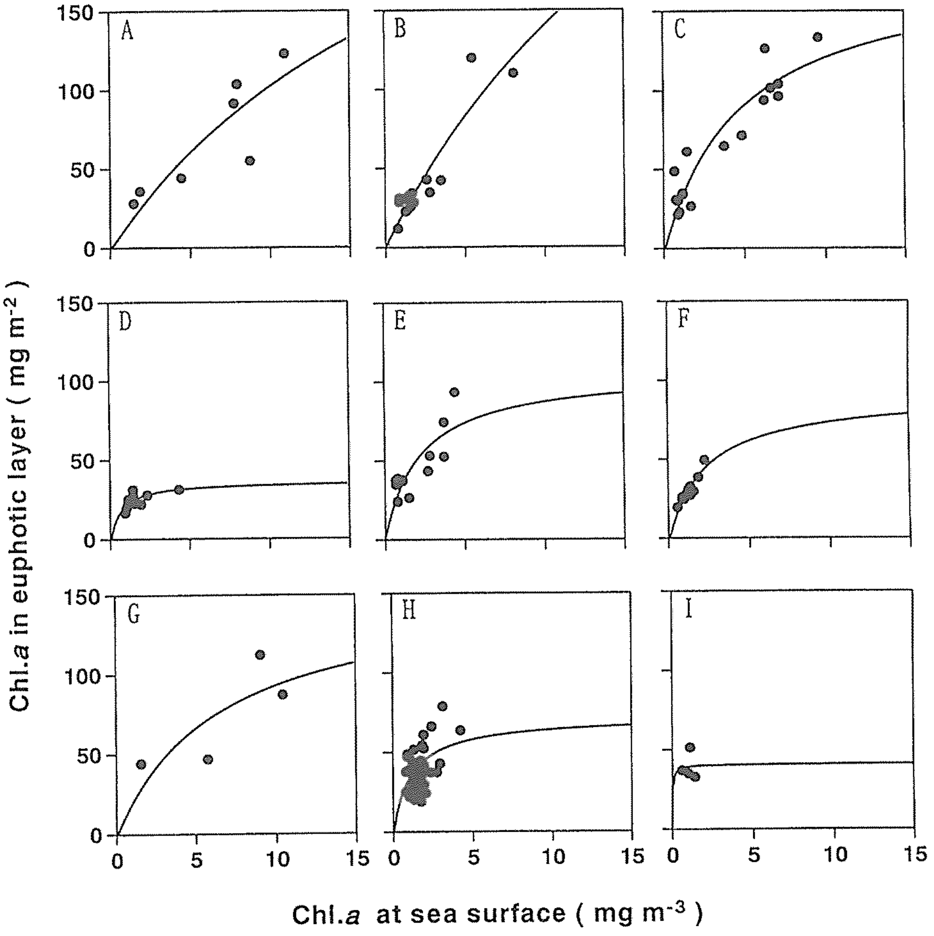

Fig. 2. Correlation between the chl.*a* concentration at the sea surface and the standing stock of chl.*a* in the euphotic layer in each sub areas.

Table 1. Mean values of chl.*a* concentration at the sea surface ($\overline{Cs}$) and standing stock of chl.*a* in the euphotic layer ($\overline{Se}$) for each sub-area. Estimated factors of C1 and C2 and correlation coefficient (r) for regression curve by using the least square maethod for each sub-area.

Sub-area	$\overline{Cs}$ (mg m^{-3})	$\overline{Se}$ (mg m^{-2})	C1 (mg m^{-2})	C2 (mg m^{-3})	r
A	6.1	69.5	327.6	21.7	0.85
B	2.4	41.7	455.8	22.6	0.92
C	3.6	65.1	176.6	4.66	0.92
D	1.7	25.6	36.5	0.61	0.67
E	2.0	46.2	106.2	2.18	0.79
F	1.2	29.4	88.8	2.22	0.90
G	6.7	73.4	155.1	6.48	0.74
H	1.6	39.2	70.2	1.17	0.56
I	1.0	39.8	41.1	0.70	0.51

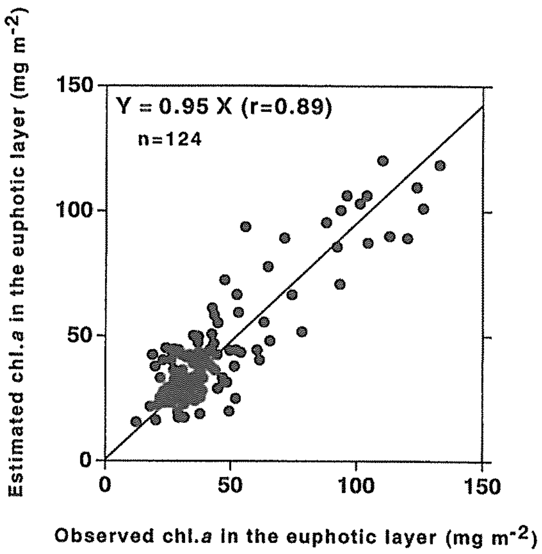

Fig. 3. Correlation between the observed standing stocks of chl.*a* in the euphotic layer and the estimated ones for all stations.

The factor C1 (mg m^{-2}) expressed the maximum of standing stock of chl.*a* in the euphotic layer for each sub-area. The factor C1 is high in the sub-areas A, B, C and G. In these areas, the density stratification developed during summer (HASHIMOTO *et al.*, 1997a) and the influences of nutrient input from land are comparatively large (HASHIMOTO and TAKEOKA, 1998). Therefore, high productivity of phytoplankton in the euphotic layer is maintained and the large capacity of the primary production can exist in these areas. On the other hand, the factor C1 is low in the areas D, F, H and I. In these areas, vertical mixing of water column predominates throughout the year (HASHIMOTO *et al.*, 1997a). Then, this result suggests that the primary production is reduced because of the low illumination experienced by the phytoplankton in these sub-areas due to the transport of the phytoplankton from the euphotic layer to the aphotic layer by the strong vertical mixing.

We estimated the standing stock of chl.*a* in the euphotic layer in all sub-areas using Eq.(4)

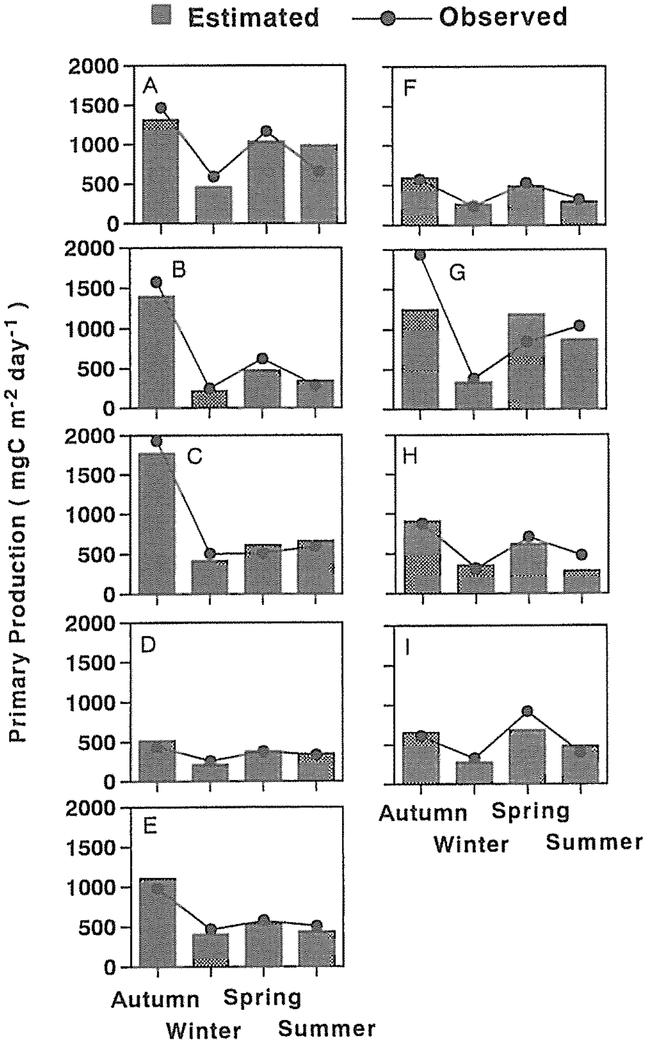

Fig. 4. Seasonal variations of primary production estimated from the chl.*a* concentrations at the sea surface, compared with the observational results of HASHIMOTO *et al.* (1997).

from the observed chl.*a* concentration at the sea surface. The relationship between the observed standing stocks of chl.*a* in the euphotic layer and the estimated ones for all stations was significant (Fig. 3; $r=0.89$, $p<0.005$).

Further, we estimate the seasonal variation of the primary production for each sub-area. The primary production for each station was calculated as the product of the estimated standing stock of chl.*a* in the euphotic layer and the ratio of primary production to chl.*a* standing stock for each season observed by TADA *et al.*(1998). The seasonal variations of the mean primary production for each sub-area are compared with observational results of HASHIMOTO *et al.*(1997a)(Fig. 4). Although there are some discrepancies, the estimated seasonal variations of primary production are quite consistent with the observed values. According to these results (Figs. 3, 4), we may reasonably conclude that the estimation of the standing stock of chl.*a* in the euphotic layer and the primary production from the chl.*a* concentration at the sea surface is actually probable in the Seto Inland Sea.

In this study, there is not enough data for the detailed analysis of the seasonal and spatial variations of the primary production. However, these results may indicate the possibility of the estimation of the primary production from the ocean color image by the satellite in the Seto Inland Sea. We will examine in detail the seasonal and spatial variations of the primary production in the Seto Inland Sea using the ocean color images by the satellite and the vertical distributions of chl.*a* in the near future.

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瀬戸内海における海表面クロロフィル *a* 濃度と有光層内クロロフィル *a* 現存量との関係

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要　旨　瀬戸内海における海表面クロロフィル *a* 濃度と有光層内クロロフィル *a* 現存量との関係を調べた．瀬戸内海を9つの海域に区分し，観測結果からその関係を明らかにした．その結果，人工衛星による海色画像から各海域の一次生産量を見積もることが可能であることが明らかになった．

キーワード：一次生産，クロロフィル *a*，有光層，衛星画像