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Modeling the Effects of Periodic Intrusions of Outer Water on the Variation in the Phytoplankton Biomass and Productivity in a Small Embayment

Hayami, Yuichi*, Shu Ougiyama[1], Tsuneyoshi Koizumi[2,3] and Hidetaka Takeoka[2]

(*Faculty of Engineering, Ehime University,* [1]*Graduate School of Science and Engineering, Ehime University,*
[2]*Center for Marine Environmental Studies, Ehime University,* [3](*present address*) *ECOH Co.LTD.*)

Effects of the different strengths and intervals of the periodic outer water intrusions (*kyuchos* and bottom intrusions) on the dynamics of phytoplankton biomass in a small embayment were examined with a simple numerical model. Environmental conditions of Kitanada Bay in the Bungo Channel were applied to the model. As the interval of the intrusion became longer and the amplitude became smaller, phytoplankton biomass in the bay became higher. On the other hand, as the interval became shorter and the amplitude became larger, the growth rate of the phytoplankton became higher. It suggested that when the intrusion was weaker, water exchange of the bay decreased and the phytoplankton in the bay accumulated at a high density. When water exchange was improved by active intrusions, availability of light would become more efficient and the growth rate of the phytoplankton was enhanced.

Key words: phytoplankton biomass, numerical model, intrusion, Seto Inland Sea

INTRODUCTION

In the Bungo Channel, located at the western end of the Seto Inland Sea, Japan, periodic intrusions of oceanic water; *kyuchos* (Takeoka and Yoshimura, 1988) and bottom intrusions (Kaneda *et al.*, 2002) occur periodically. The *kyucho* is a warm water intrusion along the surface layer from the Pacific Ocean. The bottom intrusion is a cold water intrusion along the bottom from the shelf slope. These intrusions generate large variations in phytoplankton biomass in the tributary bays and coves of this channel (Koizumi, 1999). The water intruded as the bottom intrusion contained high nitrate concentration and hence the bottom intrusion would enhance the primary production in the bay. On the other hand, since the water intruding with the *kyucho* was oligotrophic and poor in phytoplankton, hence it decreased chlorophyll *a* concentration in the bay (Koizumi and Kohno, 1994; Koizumi, 1999). The strength and the frequency of these intrusions vary year by year (Takeoka *et al.*, 2000). We examined the effect of their variations on the phytoplankton biomass in a tributary bay with a numerical model.

MODEL

A simple 2 layer box model was used for this study (Fig. 1). The model consisted of a physical sub-model and a nitrogen based ecosystem model with 3 compartments (dissolved inorganic nitrogen (DIN), chlorophyll *a* and phytoplankton nitrogen) similar to that of Tett and Jones (1986). The depth of the interface between the upper and

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* Corresponding Author: Tel: +81-89-9278997, Fax: +81-89-9279846, E-mail: hayami@dpc.ehime-u.ac.jp

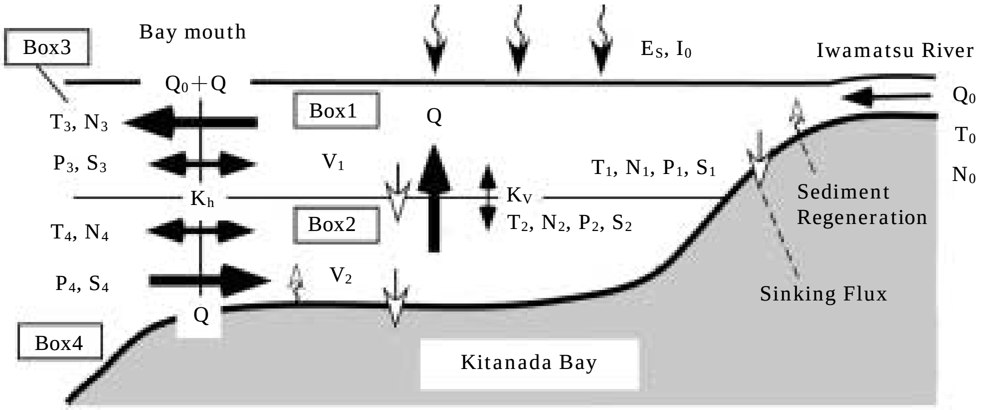

Fig. 1. Schematic of the model.

lower layers is 15 m. The variation in temperature T in the bay is calculated with the following equations,

$$V_1\frac{\partial T_1}{\partial t}=Q\frac{T_2-T_3}{2}+Q_0(T_0-T_1)+A_{v1}K_h\frac{\partial T}{\partial x}+A_{h2}K_v\frac{\partial T}{\partial z}+\frac{E_sA_{h1}\rho_1}{C_w} \quad (1)$$

$$V_2\frac{\partial T_2}{\partial t}=Q\frac{T_4-T_1}{2}+A_{v2}K_h\frac{\partial T}{\partial x}-A_{h2}K_v\frac{\partial T}{\partial z} \quad (2)$$

where V is the volume of the box, K_h and K_v are the horizontal and vertical diffusion coefficients respectively. Q is the water flux from outside the bay into the box 2 and Q_0 is the river discharge. A_{v1} and A_{v2} are the areas of the vertical interface at the bay-mouth. E_s is the surface heat flux, A_{h1} and A_{h2} are the area of surface and the interface between upper and lower layer, ρ_1 is the sea water density and C_w is the specific heat. The variation in chlorophyll *a* concentration P is described with the following equations,

$$V_1\frac{\partial P_1}{\partial t}=Q\frac{P_2-P_3}{2}-Q_0P_1+A_{v1}K_h\frac{\partial P}{\partial x}+A_{h2}K_v\frac{\partial P}{\partial z}A_{h1}wP_1+V_1(\mu_1P_1-rP_1^{G}) \quad (3)$$

$$V_2\frac{\partial P_2}{\partial t}=Q\frac{P_4-P_1}{2}+A_{v2}K_h\frac{\partial P}{\partial x}-A_{h2}K_v\frac{\partial P}{\partial z}-A_{h2}w(P_2-P_1)+V_2(\mu_2P_2-rP_2^{G}) \quad (4)$$

where w is the sinking rate of phytoplankton cells, μ is the specific growth rate, G is the grazing exponent and r is the grazing impact. According to Nakata (1993),

$$\mu=\mu_T(T)\times\mu_I(I)\times\mu_N(SQ) \quad (5)$$

$$\mu_T(T)=0.59\exp(0.0633T) \quad (6)$$

$$\mu_I(I)=\frac{1}{I_{\mathrm{opt}}}\exp\left(1-\frac{I}{I_{\mathrm{opt}}}\right) \quad (7)$$

$$\mu_N(SQ)=\left(1-\frac{SQ_0}{SQ}\right) \quad (8)$$

where I is photosynthetically active radiation (PAR), SQ is cell quota ($=S_i/P_i$, where i = 1,2 and S means phytoplankton nitrogen), I_{opt} is the optimum PAR and SQ_0 is the subsistent quota. The PAR in the water column at a depth z is described as follows,

$$I=I_0\times\exp(-kz) \quad (9)$$

where I_0 is the surface PAR and k is the attenuation coefficient. In our model, the average PAR in the box 1 and box 2 are used for the calculation. For the calculation, k is set as constant in each box and described as a function of the chlorophyll *a* concentration P. The variation in phytoplankton nitrogen S is calculated with the following equations,

$$V_1\frac{\partial S_1}{\partial t}=Q\frac{S_2-S_3}{2}-Q_0S_1+A_{v1}K_h\frac{\partial S}{\partial x}+A_{h2}K_v\frac{\partial S}{\partial z}-A_{h1}wS_1+V_1(u_1P_1-rP_1^{gr}S_1) \quad (10)$$

$$V_2\frac{\partial S_2}{\partial t}=Q\frac{S_4-S_1}{2}+A_{v2}K_h\frac{\partial S}{\partial x}-A_{h2}K_v\frac{\partial S}{\partial z}-A_{h2}w(S_2-S_1)+V_2(u_2P_2-rP_2^{gr}S_2) \quad (11)$$

where u is the nutrient uptake rate which is described with a following Michaelis-Menten function of the nutrient concentration N, cell quota SQ, the maximum uptake rate u_{max}, the maximum cell quota SQ_{max} and the nutrient concentration for half maximum uptake rate K_N.

$$u = u_{\max}\left(1-\frac{SQ}{SQ_{\max}}\right)\Big/\left(\frac{K_N+N}{N}\right) \tag{12}$$

The variation in the nutrient concentration is calculated with the following equations.

$$V_1\frac{\partial N_1}{\partial t} = Q\frac{N_2-N_3}{2}+Q_0(N_0-N_1)+A_{v1}K_h\frac{\partial N}{\partial x} + A_{h2}K_v\frac{\partial N}{\partial z}-(u_1P_1-\alpha rP_1^{gr}S_1)V_1+(A_{h1}-A_{h2})r_D \tag{13}$$

$$V_2\frac{\partial N_2}{\partial t} = Q\frac{N_4-N_1}{2}+A_{v2}K_h\frac{\partial N}{\partial x}-A_{h2}K_v\frac{\partial N}{\partial z} -(u_2P_2-arP_2^{gr}S_2)V_2+A_{h2}r_D \tag{14}$$

where α is the excreted proportion of grazed nutrient, and r_D is a sediment regeneration rate of DIN which was estimated with the relationship between the ignition loss and the nutrient release rate from the sediment in the Seto Inland Sea (Yamamoto *et al.*, 1998).

VERIFICATION OF THE MODEL

In order to validate this model, we compared the result of computation with the data observed

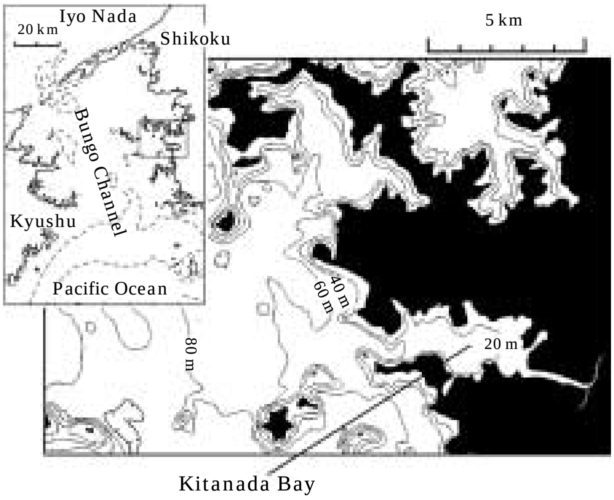

Fig. 2. Map of Kitanada Bay.

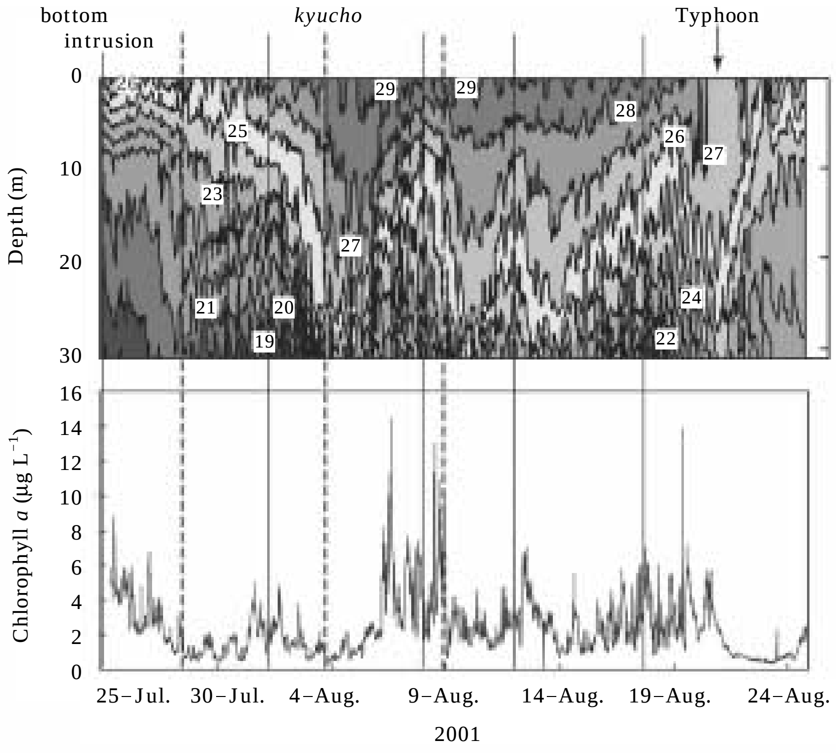

Fig. 3. Temporal variation in temperature profile (upper) and chlorophyll *a* concentration at 5 m (lower) in Kitanada Bay in 2001. Broken lines indicate *kyuchos* and solid lines indicate bottom intrusions.

in 2001 in Kitanada Bay (Fig. 2) which is a small estuary located at the eastern side of the Bungo Channel. Detailed methods of the observation are presented in Kohama *et al.* (in prep.). In this observation, measurements of water quality and CTD casts were carried out 7 times between 18 July and 17 Augst and continuous measurement of temperature, current and chlorophyll fluorescence were conducted with moorings at the mouth and the center of the bay. Fig. 3 shows that, during one month, *kyuchos* and bottom intrusions occurred repeatedly. When the *kyucho* occurred, the chlorophyll *a* concentration decreased and the bottom intrusion was followed by an increase in chlorophyll *a* concentration. The observed data or the empirical equations constructed with the observed data were used as the boundary conditions. The data observed on 18 July were used as the initial values of the state variables.

Comparison between the calculated and the observed concentrations of chlorophyll *a* shows that the basic pattern of the variation is well reproduced (Fig. 4). The extremely high concentrations in chlorophyll *a* and phytoplankton nitrogen in the upper layer on 25 July and the increase in DIN concentration after 8 August could not be reproduced. However increases in chlorophyll *a* on 25 July and 8 August associated with the bottom intrusion and the decrease on 4 August caused by the *kyucho* are reproduced. So we consider that this model can be used to test the effects of the variation in the *kyucho* and the bottom intrusion on phytoplankton biomass in the bay.

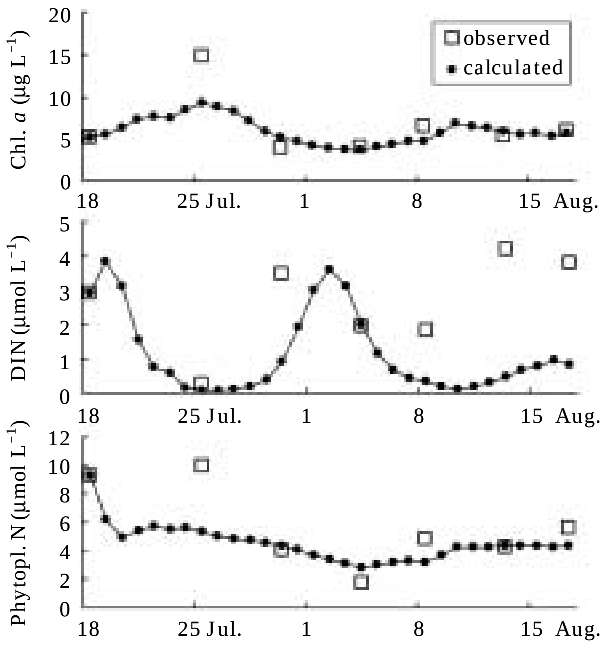

Fig. 4. Comparison between the calculated and observed chlorophyll *a*, DIN and phytoplankton nitrogen in the box 1.

NUMERICAL EXPERIMENT

In order to examine the effects of the different

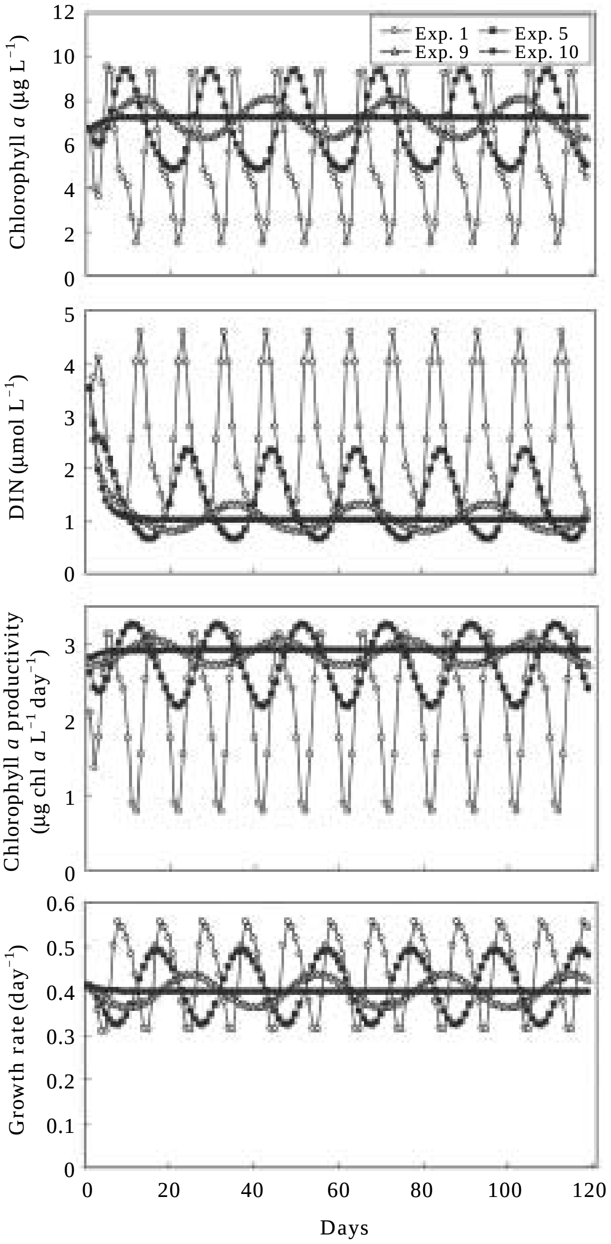

Fig. 5. The variations in chlorophyll *a*, DIN, chlorophyll *a* (primary) productivity and specific growth rate in the box 1 in case of exp. 1, 5, 9 and 10.

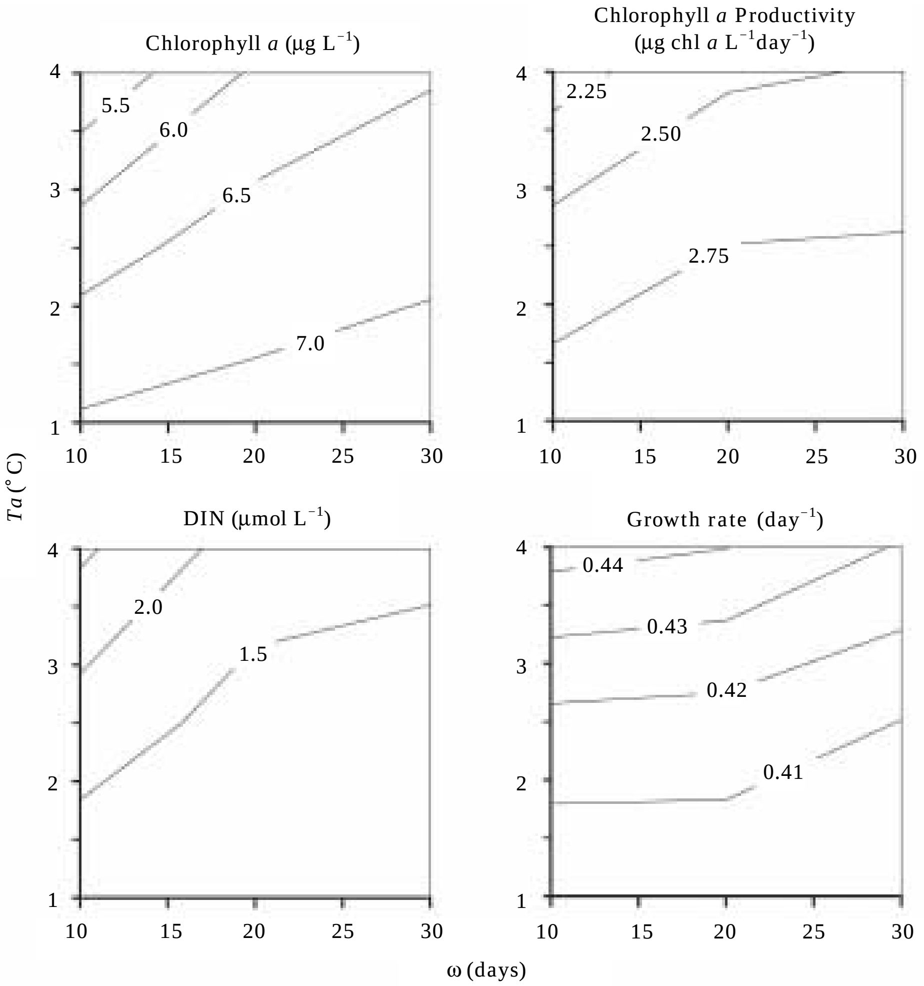

Fig. 6. Average chlorophyll *a*, DIN, chlorophyll *a* (primary) productivity and growth rate for the different intervals and strengths of intrusions. T_a is the amplitude and ω is the period of temperature variation caused by intrusions.

Table 1. Amplitude (T_a) and period (ω) of temperature variation caused by intrusions (*kyuchos* and bottom intrusions).

ω (days) / T_a (°C)	10	20	30
4	Exp. 1	Exp. 2	Exp. 3
2.5	Exp. 4	Exp. 5	Exp. 6
1	Exp. 7	Exp. 8	Exp. 9
0	Exp. 10		

strengths and intervals of the intrusions (*kyuchos* and bottom intrusions), we made 10 cases of the experiment (Table 1). In these cases, the discharge, temperature and DIN concentration of the river are set constant ($Q_0 = 0.2 \times 10^6$ m^3 day^{-1}, $T_0 = 25.7$°C and $N_0 = 34$ μmol L^{-1}) and a diurnal cycle of PAR was used based on the average values of the observation in 2001. Average value of the 2001 observation was also used for surface heat flux. The bay mouth temperature was provided by the following equation to express the periodic occurrence of *kyuchos* and bottom intrusions,

$$T = T_a \sin\left(2\pi\frac{t}{\omega}+\pi\right)+T_m \tag{17}$$

where T_m is the average temperature and T_a is the amplitude and ω is the period of temperature variation caused by intrusions. T_m in the upper and lower layers are 25.4 and 22.5°C respectively. They are the average values of the 2001 observation. The DIN, chlorophyll *a* and phytoplankton nitrogen concentration at the bay mouth are expressed as the function of temperature. The water flux at the bay mouth Q was provided as the function of the bay mouth temperature as follows.

$$Q = 1.4952 \frac{dT/dt}{dT/dz} - 57.873 \tag{18}$$

according to the relationship between the bay mouth temperature and the water flux during the observation in 2001. The initial values of the state variables in boxes 1 and 2 are equal to those in boxes 3 and 4 (e.g. T_1, $T_3 = 25.4$°C; T_2, $T_4 = 22.5$°C). The calculation was carried out for 120 days. As the variations became steady after 30 days (Fig. 5), the average data between 31 to 120 days was used to represent the cases.

The average chlorophyll *a* and chlorophyll *a* productivity (primary productivity) were highest in the exp. 10, and decreased with shorter interval and larger amplitude of the intrusion (Figs. 5 and 6). Conversely, the average DIN and growth rate were lowest in exp. 10, and increased with shorter interval and larger amplitude (Figs. 5 and 6).

DISCUSSION

In Kitanada Bay, average phytoplankton biomass in summer was relatively high in years when bottom intrusion was active (Hayami *et al.*, in press). The nutrient supply by bottom intrusions would sustain high production of phytoplankton. However the effects of the intrusions should be evaluated not only from the chemical aspects but also from the physical ones. The results of the present numerical experiments showed that when the average conditions at the bay mouth (e.g. nutrient concentration) are set same, active intrusions lessen the phytoplankton biomass and production in the bay because phytoplankton are flush out before reaching at a high density. When intrusions are inactive, the water exchange is weak and the phytoplankton in the bay become abundant. In the coast of the Bungo Channel, red tides occur sometimes when *kyuchos* are inactive (Koizumi *et al.*, 1996). This agrees with the result of our experiments. Even if the average nutrient concentration is high, highly active occurrences of intrusions would lessen the phytoplankton production and biomass. Contrary to the phytoplankton productivity, the growth rate of the phytoplankton was enhanced due to the active intrusions. It was because the lower concentration of phytoplankton allows the higher PAR in the water column.

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<국문적요>

작은 만에서 식물플랑크톤 생체량과 생산력 변화에 대한 외부 물의 정기적인 침입 효과의 모델링

Hayami, Yuichi, Shu Ougiyama[1], Tsuneyoshi Koizumi[2,3] and Hidetaka Takeoka[2]

(*Faculty of Engineering, Ehime University*
[1]*Graduate School of Science and Engineering, Ehime University*
[2]*Center for Marine Environmental Studies, Ehime University*
[3](*present address*) *ECOH Co.LTD.*)

본 연구는 Kitanada 만에 있어서 식물플랑크톤 생체량의 변동기구에 대한 세기와 주기성이 다른 두 가지 형태의 외양수유입(急潮 및 bottom intrusion)의 영향을 만의 환경조건을 고려한 수식모델을 이용하여 분석하였다. 외양수 유입의 간격이 길어지고 진폭이 작아짐에 따라 만 내의 식물플랑크톤 생체량이 커졌으나, 이와는 반대로, 유입간격이 짧아지고 진폭이 커질수록 식물플랑크톤의 성장률은 높아졌다. 이 결과는 유입이 약해짐에 따라 만의 해수교환이 감소하고 만내의 식물플랑크톤이 높은 밀도로 축적됨을 시사하였다. 또한, 외양수유입에 의해 해수교환이 활발해짐에 따라 빛의 효율적 이용이 가능하여 식물플랑크톤의 성장률이 향상되었다.