D－1.3.1. Development of Ecological Model for Element Cycle in East China Sea

Contact Person Masataka Watanabe
Director
Division of Water and Soil Environment
National Institute for Environmental Studies
Environment Agency
16-2 Onogawa, Tsukuba, Ibaraki 305-0053, Japan
Tel:+81-298-50-2338 Fax: +81-298-50-2576
E-mail: masawata@nies.go.jp

Total Budget for FY1996 - FY1998 26,240,000 Yen (FY 1998; 3,723,000 Yen)

Abstract

Based on marine mesocosm experiment conducted from Oct. 10 to Oct. 17, 1997, in Changjiang Estuary, ecosystem model was developed. It was found that photosynthetic pathways was composed of diatom (Skeletonema, Chaetoceros) and copepod (Paracalanus, Oithona, Microsetella), and that bacterial pathway was composed of bacteria, picoplankton and Appendicularia (Oikopleura). Ecosystem model expressing phytoplankton succession of diatom and dinoflagellate, grazing by zooplankton, nutrient dynamics, microbial loop including bacterial and photosynthetic pathways was included for Changjiang estuary. The model was described by vertically one dimensional mass conservation equation with 15 independent variables including N, P, Si in dissolved matter and particulate biota of phytoplankton, picoplankton, bacteria and zooplankton. The model was validated by measured data of marine mesocosm experiment in Changjiang estuary.

Key Words: Ecosystem model, element cycle, Changjiang estuary, bacterial pathway, photosynthetic patyway

1. Introduction

The Changjiang river is the major source of freshwater, sediments and nutrients that flow into the East China Sea and the northeastern Pacific ocean, which is one of the most productive oceanic shelves in the world in terms of biodiversity and standing stocks. The highest values of phytoplankton standing stock and production were generally located on the continental shelf more than 100 km away from the river mouth where salinity was in the range of 25~30‰. Dominant phytoplankton was diatom and photosynthetic productivity was controlled by light penetration due to high turbidity caused by sediment supply from Changjiang river, despite of high nutrient concentration. Distribution of nutrients in the Changjiang estuary and East China Sea were controlled by two ware masses, diluted water from the Changjiang river and offshore water of the East China Sea, and ecosystem succession was controlled by the change in the ratio of N: P: Si.

Ecosystem model was developed based on element cycle through ecosystem and was calibrated by mesocosm experiment in the Changjiang estuary.

2. Ecosystem structure.

Mesocosm experiment with phosphorous enrichment was carried out in the Changjiang

estuary from Oct.10~17, 1997. Oceanographical conditions of turbidity and temperature distributions during the mesocosm experiment were analyzed by using NOAA-AVHRR data (Fig. 1a, b). Highly turbid water from the Changjiang river was spread along the coast of China in north and in south direction toward Amoy (Xiamen). Mesocosm was installed 100km offshore from Shanghai, where located aroud the frontal zone and ecosystem was released from light limitation after sedimentation of particles supplied from turbid water. Temperature around mesocosm site was about 23℃ with good agreement with observed data.

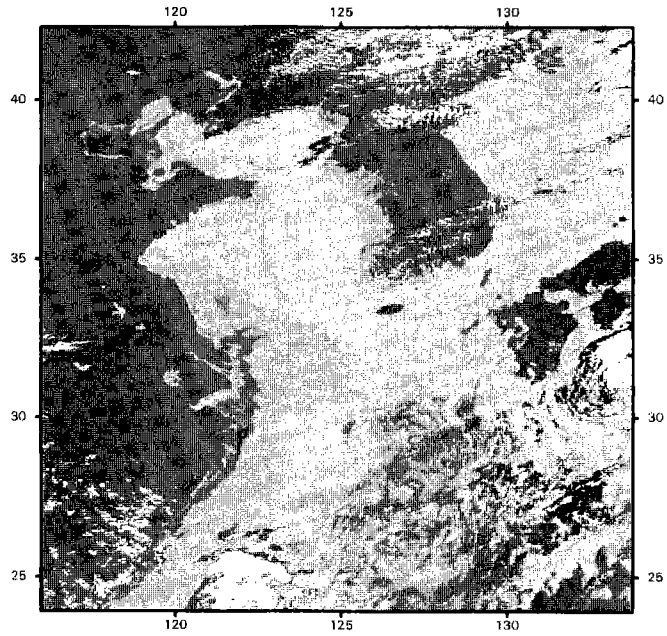

Fig 1a. Turbidity index distribution using NOAA-AVHRR data (1997. 10. 17)

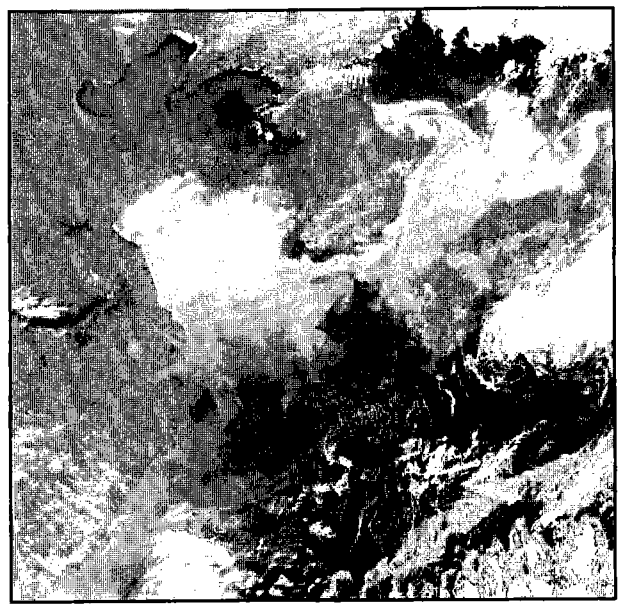

Fig1b. Temperature distribution using NOAA-AVHRR data (1997. 10. 17)

After the phosphate enrichment, blooms of a phytoplanktonic diatom (*Skeletonema costatum*) was observer in 1997. With development of the blooms, nitrate (initial concentration ca 24 and 16 μM, respectively) rapidly decreased together with the added phosphate and became depleted. Silicate concentration fell from ca 40 μM to ca 1 μM in which the bloom of *S. costatum* was observed.

The dominant predators that increased in number as a result of the phytoplankton bloom were largely in appendicularians followed a gradual increase in copepods. Tracer experiments with inorganic ^{13}C showed that the percentages of ^{13}C transferred to >100-μm particles (i.e. the fraction of metazooplankton assemblages) increased in proportion to the increase in metazooplankton abundance, and the values were higher than 10%. Appendicularians are incapable of ingesting large diatoms like *S. costatum*; thus, the high percentage of label transfer was probably due to ingestion of diatoms by copepods (Fig.2.). The diet of the appendicularians was likely to have included not only photosynthetic production but also bacteria to a large extent, because appendicularians are able to ingest pico- and nano-sized particles only (Fig. 3.). The proportions of organic ^{13}C tracer became markedly higher in the 20- to 100 μm and/or >100-μm fractions when appendicularians increased in number. Element cycle of nitrogen and phosphorous were therefore associated with carbon cycle through ecosystem (e. g. primary production→grazer →

decomposition → bacterial production →grazer), and ecosystem model in Changjiang estuary can be expressed as Fig. 4.

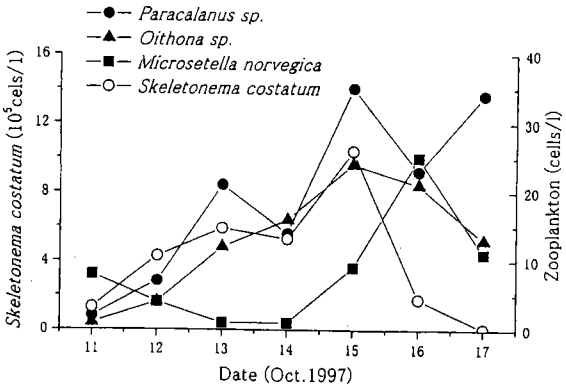

Fig. 2. Variation f diatom and copepod population

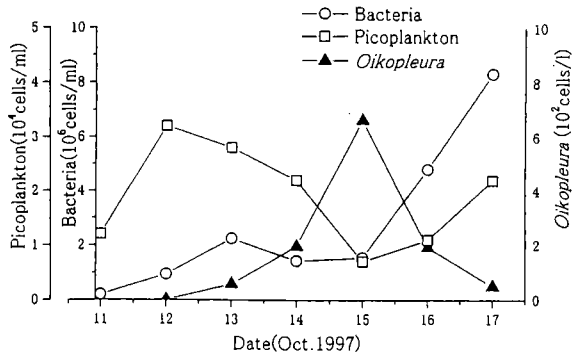

Fig. 3. Variation of bacteria, picoplankton and Appendicularia population

3. Ecosystem model

The ecosystem model expresses phytoplankton succession of diatom (Skeletonema, Chaetoceros) and dinoflagellate (Ceratium, Prorocentrum), grazing by microzooplankton and zooplankton, nutrients (N, P, Si) dynamics, bacterial and photosystheic pathways (Fig. 4). The model was described by vertically one dimensional mass conservation equations with 15 independent variables including PO_4^{2-}, NO_3^-, NH_4^+, $Si(OH)_2$, cell concentrations of diatom, dinoflagellate, picoplankton, P cell quota and N cell quota of diatom, dinoflagellate and picoplankton, Si cell quota of diatom, cell concentration of bacteria as follows;

$$\frac{\partial C_i}{\partial t} = -\frac{1}{A}\left[\frac{\partial}{\partial z}(Q_V \cdot C_i) + \frac{\partial}{\partial z}(V_{M_i} \cdot A \cdot C_i) + \frac{\partial}{\partial z}\left(A \cdot E \cdot \frac{\partial C_i}{\partial z}\right)\right]$$

Vertical advection — DVM — Dispersion

$$+ (\text{Change by the activity of biological production}) + \frac{U_I \cdot C_i^0}{A} - \frac{U_O \cdot C_i}{A} \qquad (1)$$

Horizotal advection

where Q_v is the vertical flowrate, or $\int^{z}_{o} [U_i(z,t)-U_o(z,t)]dz$,$U_i$ is the horizotal inflow velocity, U_o is the horizontal out-flow velocity, A is the horizontal cross sectional area of control volume, C^o_i is the concentration of component i (inflow), E is the vertical dispersion coefficient. The growth rate of marine phytoplankton can be represented as a function of factors such as water temperature (T), irradiation(I), and intracellular nutrient concentration (Q^i)of nutrient i (cell quota). Growth, is controlled by the intracellular concentrations of nitrogen and phosphorus just before cell division, temperature, and irradiation. Thus, the growth rate can be evaluated as a function of these parameters:

$$\mu = f(T, I, Q^N, Q^P)$$
$$\cong f_1(T) \cdot f_2(I) \cdot f_3(Q^N, Q^P) \qquad (2)$$

The relationship between growth rate and cell quota of N and P before cell divison can

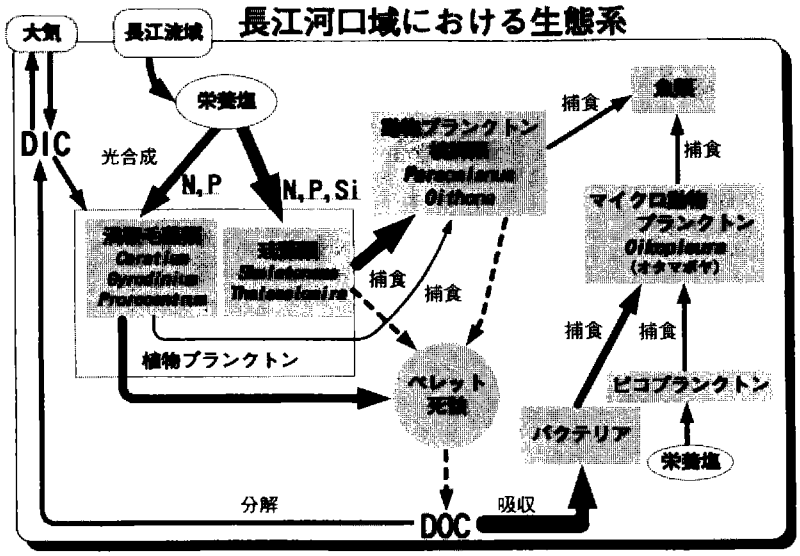

Fig. 4. Ecosystem in Changjiang estuary

be expressed by Droop's

$$\mu_P = \mu_P^*(1 - q_0^P / Q^P) \quad (3)$$

$$\mu_N = \mu_N^*(1 - q_0^N / Q^N) \quad (4)$$

where μ_N is the specific growth rate under N limitation, μ_P is the specific growth rate under P limitation , q_0^P is the minimum N cell quota, q_0^P is the minimum P cell quota, μ_N^* is the maximum growth rate obtained by making cell quota of N (Q^N) infinite, and μ_p^* is the maximum growth rate obtained by making cell quota of P(Q^P) infinite.

Because the values of μ_N and μ_P were determined under conditions in which only one nutrient always controlled the growth rate, the growth rate of phytoplankton is not clear when either N or P is growth limiting according to variation in the N:P ratio. Rhee (1978) proposed the following equation for estimating the growth rate under such conditions:

$$f_3 = \min [\mu_N, \mu_P] \quad (5)$$

Among several models of the temperature effects on algal growth, developed by Lamanna and Mallette(1965).

$$f_1(T) = \left(\frac{T - T^*}{T_{opt} - T^*}\right)^n \exp\left[1 - \left(\frac{T - T^*}{T_{opt} - T^*}\right)^n\right] \qquad T^* \leqq T \leqq T_{opt}$$

$$f_1(T) = 1 - \left(\frac{T - T_{opt}}{T_{max} - T_{opt}}\right)^{m1} \qquad T_{opt} \leqq T \leqq T_{max} \quad (6)$$

where T* is the threshold temperature for growth, T_{opt} is the optimum temperature for growth, T_{max} is the maximum temperature for growth, and n and m_1 are dimensionless

parameters characteristic for algal species.

From several models of the influence of light intensity on algal growth, we modified the one described by Bannister (1979)

$$f_2(I) = \frac{i/i_k}{\left[1+(i/i_k)^{m2}\right]^{1/m2}} \qquad (7)$$

where I* is the threshold irradiation for growth, I_K is the irradiance at which growth rate saturates, i equals I – I*, i_K equanls I_K - I*, and m_2 is a dimensionless parameter characteristic for algal species.

The uptake rate of ammonium and nitrate by phytoplankton can each be described by simple Michaelis-Menten equation if each salt exists in the medium alone, suggesting that the influence of cell quota on uptake is minimal. However, the coexistence of multiple forms of nitrogenous nutrients, such as nitrate and ammonium, require a more complex Michaelis-menten formulation. When such forms coexist in the medium, the uptake rate of ammonium is not affected by the presence of nitrate; however ammonium hinders the uptake of nitrate.

$$V_p = V_{PO_4} = V_{max}^{PO_4} \frac{S_{PO_4}}{K_S^{PO_4} + S_{PO_4}} \qquad (8)$$

where $V_{max}^{PO_4}$ is the maximum phosphate uptake rate, $K_S^{PO_4}$ is the half-saturation concentration for phosphate uptake, and S_{PO4}, is the ambient phosphate concentration.

$$V_N = V_{NH_4} + V_{NO_3}$$
$$= V_{max}^{NH_4} \frac{S_{NH_4}}{K_S^{NH_4} + S_{NH_4}} + \frac{1}{1+\frac{S_{NH_4}}{K_I}} V_{max}^{NO_3} \frac{S_{NO_3}}{K_S^{NO_3} + S_{NO_3}} \qquad (9)$$

where $V_{max}^{NH_4}$ and $V_{max}^{NO_3}$ are the maximum uptake rates of NH_4^+ and NO_3^-, $K_S^{NH_4}$ and $K_S^{NO_3}$, are the half-saturation concentrations for $NH_4^+$and NO_3^-, K_I is the inhibition constant, and S_{NH4} and S_{NO3} are ambient concentrations of NH_4^+ and NO_3^-.

Table1. Growth parameters for phytoplankton

	P				N				Si			
	q_0	Ks	Vmax	Mmax	q_0	Ks	Vmax	Mmax	q_0	Ks	Vmax	μ max
unit	Pmol／cell	MM	pmol／cell･hr	1／d	Pmol／cell	μ M	pmol／cell･hr	1／d	Pmol／cell	μ M	pmol／cell･hr	1／d
Diatom	0.002	0.1	0.003	2.0	0.04	1.5	0.04	2.0	0.5	7.0	0.7	2.0
Dinflagellate	0.01	1.0	0.03	1.0	0.2	2.0	0.15	1.0	0			
Picoplankton	0.36 E-9	0.1	0.5 E-9	2.0	3.6 E-9	1.5	5.0 E-9	2.0				

3-3 Bacteria model

The fundamental equation for the growth of bacteria is given as follow (Baretta and Ruardiji, 1988)

$$\frac{dB}{dt} = (G_B - R_B) * B \qquad (10)$$

B = bacteria biomass $(\mu gC \cdot L^{-1})$

G_B = specific uptake rate of bacteria (d^{-1})

$= Vm_B \cdot F(T) \cdot F(O2)$

Vm_B = maximum uptake rate = 6.3 (d^{-1})

$F(T)$ = temperature effect = $2^{[T-12.0]/10}$

T = seawater temperature

$F(O2)$ = oxygen reduction effect = $\dfrac{eO2}{KO2 + eO2}$

$eO2 = \min(1, O2/O2S)$

O 2 = the state variable for oxygen (μ mol O $\cdot$ L^{3-})

O2S = the actual oxygen saturation, which is temperature dependent

KO2 =oxygen saturation where respiration is depressed to 0.5 its level at 100% oxygen saturation R_B = specific loss rate due to respiration (d^{-1}) (11)

$= 0.2 * \cdot F(T) + [1 - effM * eO2 - effMa(1 - eO2)] * G_B$

effM = ratio between consumed substrate by respiration and by uptake under aerobic condition = 0.3

effMa = ratio between consumed substrate by respiration and by uptake under anaerobic condition = 0.2

Carbon content in bacteria is in the range of 0.08 ~ 0.2pgC $\cdot$ μ m^{-3}(Watson et. al., 1977, Nagata, 1986, Kogure and Koike, 1987). Average carbon content and diameter of bacteria is assumed to be 0.15 pgC $\cdot$ μ m^{-3} and 0.6 μ m, respectively, and carbon content of bacteria cell is 17fgC $\cdot$ $cell^{-1}$. By using this carbon content, carbon uptake rates for marine mesocosm experiment in the Changjiang estuary are 2 ~ 5 times lager than measured values (Table 2). However, considering of 4 hrs in-situ incubation with glucose as substrate enriched, the predicted values for carbon uptake rate are reasonable.

Table 2. Validation of bacterial growth model

Day	Temp (℃)	Sal (‰)	DO (ml/l)	Bacteria ($\times 10^9$ cells/L)	Bacteria (μgC/L)	G_B–R_B (1/d)	predicted uptake rate (μgC/L/h)	measured uptake rate ($\mu g^{13}C$/L/h)
0	—	—	—	—	—	—	—	—
1	—	—	—	0.196	3.332	—	—	—
2	22.8	25.0	7.68	0.930	15.81	3.456	2.2	0.68
3	23.0	25.0	7.65	2.2.41	38.097	3.456	5.5	1.36
4	23.1	25.1	7.79	1.423	24.191	3.509	3.5	0.68
5	23.4	25.8	7.23	1.538	26.146	3.497	3.8	—
6	23.4	25.8	7.23	4.811	81.787	3.497	11.9	3.8
7	22.6	26.4	6.85	8.327	141.559	3.225	19.0	10.9

3.4 Grazing by zooplankton

Grazing of phytoplankton by zooplankton is important for energy flow through photosynthetic pathway and also grazing of picoplankton and bacteria by microzooplankton is another energy flow through bacterial pathway. Grazing by zooplankton can be expressed by Monod equation as follow,

$$Graz = G_M * \max\left[0, \frac{B - B^*}{K_{SB} + B - B^*}\right] * Z$$

G_M = maximum ingestion rate

B = cell concentrations of bacteria, picoplankton, dinoflagellate and diatom

B^* = threshold

Z = cell concentrations of zooplankton

According to the field observation of grazing by Oikopleura sp. (Nakamura, 1998), ave. 15 μ gC·l^{-1}· d^{-1} of picoplankton and bacteria was ingested by Oikopleura sp. (ave. 20 ~ 30 ind·l^{-1}). Assuming carbon contents of picoplankton (250×10^{-9} μ gC·cell^{-1}; Kana and Glibert, 1987) and bacteria (17×10^{-9} μ g C·cell^{-1}) grazing rates by Oikopleura sp. were 2×10^6cells·ind^{-1}·d^{-1} for picoplankton and 30×10^6cells·ind^{-1}·d^{-1} for bacteria. Ks_{bac} and Ks_{pico} were assumed to be 1.5×10^5, 0.5×10^4, respectively.

3-5. Results and discussion

The model was applied to the mesocosm experiment conducted for Oct. 10 ~ Oct. 17, 1997, using 10 layers and Δz= 0.5m. Initial values were given from measured values of Oct. 10, 1997 and cell concentrations of microzooplankton and zooplankton were externally given from measured values. Maximum ingestion rate and threshold of picoplankton and bacteria were set to 1/10 of initial values after 4th day, in order to take into account the effect of decreasing ingestion efficiency of picoplankton and bacteria due to growth of trunk length.

Sinking velocity of diatom was set as 0.5m·d^{-1} during the period of N·P abundance, 1.0 m·d^{-1} at the 5th day when N·P was depleted and 3.0m·d^{-1} at the 6th day when N·P was completely starved.

Water sampling was conducted at the depth of 1m and therefore the predicted values at the second layer were compared with measured values. Predicted values of N, P, Si showed excellent agreement with measured values and nutrient dynamics were well simulated (Fig.5.)

Dynamics of S. costatrem and picoplankton were well simulated, but dynamics of bacteria needed some improvement(Fig.5). In particular, ingestion rate of bacteria by Oikopleura sp. might be smaller compared with ingestion rate of picoplankton, because bacteria was smaller compared with ingestion rate of picoplankton.

Ecosystem model predicted successfully the observed values of ecosystem components in Changjiang estuary. Growth of zooplankton was not included in this model but

photosynthetic and bacterial pathways were well simulated. Dynamic response of ecosystem upon the perturbation, such as nutrient input through the Changjiang river, could be predicted.

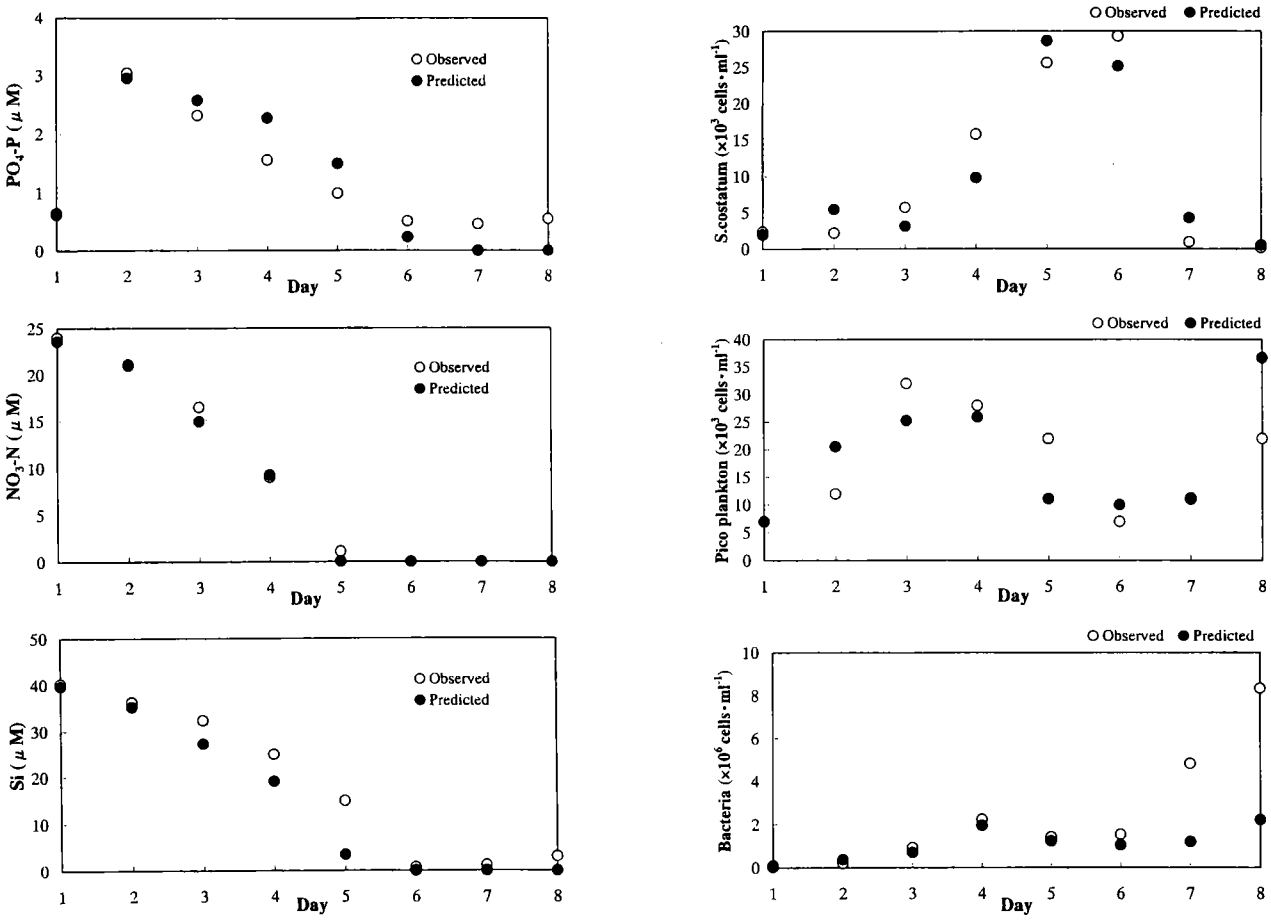

Fig. 5. Comparison between predicted and measured values

Reference

Baretta, J.W. and Ruardij, P. 1988. Tidal Flat Estuaries Simulation and Analysis of the Ems Estuary. ed. Baretta, J. and Ruardij, P. Springer - Verlag, Berlin Heidelberg.

Deibel, D. and Lee, S.H. 1992. Retention efficiency of sub-micrometer particles by the pharyngeal filter of the pelagic tunicate Oikopleura vanhoeffeni. Mar. Ecol. Prog. Ser. 81: 25-30.

Droop,M.R.(1973) Some thoughts on nutrient limitation in algae. *J. phycol.*, **9**, 264-272.

Ducklow,H.W., Purdie,D.A., Williams,P.J.L. and Davies,J.M.(1986) Bacterioplankton: a sink for carbon in a coastal marine plankton community. *Science,* **232**, 865-867.

Es, F.D. van and Meyer-Reil, L.A. 1982. Biomass and metabolic activity of heterotrophic marine bacteria. Adv. microb. Ecol.b:111-170.

Hopcroft,R.R. and Roff,J.C.(1995)Zooplankton growth rates: extraordinary production by the larvacean *Oikopleura diocica* in tropical waters. *J. Plankton Res.*, **17**, 205-220.

Kana, T.M. and Glibert, P.M. 1987. Effect of irradiances up to 2000 $\mu E \cdot m^{-2} \cdot S^{-1}$ on marine Synechococcus WH 7803-I. Growth, rigmentation and cell composition. Deep - Sea Research. 34: 479-495.

Kogure K. and Koike I. 1987. Pariticle counter determination of bacterial biomass in seawater Appl. Environ. Microbiol. 53: 274-277.

Nagata T. 1986. Carbon and nitrigen content of natural planktonic bacteria. Appl. Environ. Microbiol. 52: 28-32.

Nakamura, Y. 1998 Blooms of tunicates Oikopleura spp. and Dolioletta gegenbauri in the Seto Inland Sea, Japan, during summer. Hydrobiologia 385: 183-192.

Nakamura,Y., Suzuki,S. and Hiromi,J.(1997) Production of *Oikopleura diocica* (Appendicularia) following a picoplankton 'bloom' in a eutrophic coastal area. *J. Plankton Res.* **19**, 113-124.

Smayda, T. J. 1970. The suspension and sinking of phytoplankton in the sea, Oceanogr. Mar. Biol. Ann. Rev. 8, 353-414.

Uye,S. and Ichino,S.(1995) Seasonal variations in abundance, size composition, biomass and production rate of *Oikopleura diocica* (Fol) (Tunicata: Appendicularia) in temperate eutrophic inlet. *J. Exp. Mar. Biol. Ecol.*, **189**, 1-11.

Watson, S. W., T. J. Novitsky, H. L. Quinby, and F. W. Valois. 1977. Determination of bacterial number and biomass in the marine environment. Appl. Environ. Microbiol. 33:940-946.

Xiuren, N., Vaulot,D., Zhensheng,L. and Zilin, L.(1988) Standing stock and production of phytoplankton in the estuary of the Changjiang (Yangte River) and the adjacent East China Sea. *Mar. Biol. Ecol. Prog. Ser.* **49**, 141-150.