Ecosystem models for the three regional problems in the Northern Pacific

Michio J. KISHI\textsuperscript{1} and Michio KAWAMIYA\textsuperscript{2}

\textsuperscript{1}Ocean Research Institute, University of Tokyo, Minamidai 1-15-1, Nakano-ku, Tokyo 164, Japan
\textsuperscript{2}Center for Climate System Research, University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo 153, Japan

Abstract—On the processes to investigate a proper models for understanding the processes that govern the ocean biochemical cycle, we made three case studies (1) ecosystem model in warm core rings (2) ecosystem model in square ocean that simulate northern Pacific (3) one dimensional ecosystem model that is applied to Station papa.

(1) In order to simulate the response of the primary production dynamics to the decay of the Warm-Core Ring (WCR) 86-B off the east coast of Japan, we made a numerical model which consists of a three dimensional physical model (modified GCM) and the same biological model that FRANKS \textit{et al.} (1986) did. According to the three dimensional model, the well known sub-surface chlorophyll maximum was reproduced but horizontal distributions of chl.a and NO\textsubscript{3}-N showed different patterns corresponding to different initial conditions of nutrient. This is because the weak vertical velocity in the WCR doesn’t play an important role on the ecosystem but only the light intensity and the balance between uptake and vertical diffusion of dissolved nutrient is important. This result differs from that of FRANKS \textit{et al.} (1986).

(2) In order to simulate a carbon flux in the Northern Pacific, we made a numerical model which consists of a three dimensional physical model (modified GCM) and the biological model with four compartments. According to the calculated results, the vertical fluxes of Particulated Organic Carbon (POC) under euphotic layer is guessed to be 22 mgN m\textsuperscript{-2}d\textsuperscript{-1} which shows the same order to the observation result by NORIKI and TSUNOGAI (1986).

(3) In order to make more accurate biological model, we made an ecosystem model with seven compartments and coupled it with a one dimensional mixed layer model for calculating diffusion coefficient which appears in the governing equations and applied it to Station papa. According to the calculated results, the model could reproduce characteristic features at Station papa such as the ammonium maximum, dissolved oxygen maximum and total yearly production.

INTRODUCTION

Oceanic ecosystem plays an important role on biogeochemical cycles. If it were not for it, atmospheric CO\textsubscript{2} concentration required to reach the equilibrium state would be three times as high as the present one (SHAFFER, 1993). It is necessary to make a proper model for understanding the processes that govern the ocean biochemical cycle. BACASTOW and MAIER-REIMER (1990) and MAIER-REIMER (1993) studied
on the global carbon cycle using an ocean general circulation model (OGCM) which incorporated the function of marine ecosystem. In their models, however, the treatment of biological processes is so simplified that, for example, the dynamics of mixed layer and that of marine ecosystem are decoupled. In addition, biological production can occur only in the upper 112.5 m layer in the model while in the actual ocean the depth where production can be found varies in time and space. Indeed MAIER-REIMER (1993) stated in his paper that “we have preliminary indications that the implementation of Fasham type plankton model serves to reduce substantially the apparent flows...” referring FASHAM et al. (1993) and SARMIENTO et al. (1993).

The ecosystem models in these models are not self-consistent except FASHAM et al. (1993)’s one. It is of urgent necessity for the research of climate change and the response of ecosystems to construct the self-consistent ecosystem models which can be applied all over the world ocean. In this study we constructed various types of ecosystem model which will be incorporated into OGCM in the future. First we applied a self-consistent ecosystem model to warm core ring ecosystem, second to square ocean which imagines North Pacific and third we made a mixed layer model coupled with ecosystem model. We used different ecosystem models corresponding to the above three cases in order to compare our results with past model researches in each field respectively.

PART 1—ECOSYSTEM MODEL IN WARM CORE RING

The warm core rings off Sanriku district are associated with Kuroshio and Tsugaru currents (KAWASAKI and SUGIMOTO, 1984) and formed almost every year. Once a warm core ring (WCR) is formed, it maintains the structure during more than two years decaying or enhancing alternatively. Its decay is considered due to friction and/or diffusion, and its enhancement due to occasional intrusions of warm filaments from Kuroshio into the WCR (KAWAI and SAITO, 1986) and/or ring-ring interaction (YASUDA et al., 1992).

SUGIMOTO and TAMEISHI (1992) pointed out that a high concentration of the pacific sardine is observed around WCRs accompanied by warm filaments and this suggests that high productivity and high concentration of food exist around WCR. TRANTER et al. (1983) noted high phytoplankton productivity around WCRs off Australian current and YENTCH and PHINNEY (1985) pointed out that this high productivity around WCRs may be caused by entrainment of nutrient rich water from the surrounding region. FRANKS et al. (1986) constructed a time-dependent, two dimensional \((r, z, t)\) model incorporating a flow field calculated from an empirically derived steam function. They showed that the high new production can be calculated at the subsurface chlorophyll maximum layer, especially at the ring center the high chlorophyll concentration is reproduced.

According to the observation across 86-B off Sanriku district (Fig. 1; redrawn from LI and SUGIMOTO, 1989), the high concentration of chlorophyll can be seen at the edge of WCR rather than the ring center. The high concentration of chlorophyll at the ring center calculated by FRANKS et al. (1986) is due to the high value of the continuous upwelling near the ring center. This upwelling seems to be set unnaturally large because of their two dimensional model system.
Fig. 1. Observed chl.α (upper) in mg m⁻³ and NO₃⁻-N (lower) in µM across WCR 86B, in Sep., 1987 (redrawn from Li and SUGIMOTO, 1989).
The purpose of the present study is to ascertain FRANKS et al. (1986)’s results using the ecosystem model coupled with the three dimensional time-dependent dynamical model. The detailed results are shown with a ring-ring interaction ecosystem model in YOSHIMORI and KISHI (1994) and KISHI (1994).

**Formulation of models**

As a physical model, we used the ORI version (developed by staffs of Ocean Research Institute, University of Tokyo) of the three dimensional primitive equation for the ocean circulation, developed originally at the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ.

The one WCR model extends over a 500 km square ocean with flat bottom, the depth of which is 2500 m, bounded all around by solid, no-slip walls. There are 13 vertical levels centered at 5, 15, 25, 35, 45, 55, 70, 100, 220, 380, 520, 840, 1960 m. The horizontal grid spacing is 12.5 km. The horizontal extent is not enough to allow the model to include the actual coastline of Sanriku district, but it is enough to grasp the characteristics of the WCR ecosystem in this area.

The equations of the model are the nonlinear conservation equations which govern the change in momentum, density, and three chemical and/or biological tracers in the incompressible fluid. The eddy viscosities in the horizontal and vertical directions are \( 2.0 \times 10^6 \, \text{cm}^2\text{s}^{-1} \) and \( 10.0 \, \text{cm}^2\text{s}^{-1} \) respectively, while the eddy diffusivities in the two directions are \( 1.0 \times 10^6 \, \text{cm}^2\text{s}^{-1} \) and \( 1.0 \, \text{cm}^2\text{s}^{-1} \) respectively. (In order to avoid the instability due to the initial forcing, those are set to be ten times of the above mentioned values up to 1.0 day from the initial state.)

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**Fig. 2. Conceptual diagram of ecosystem model of Part 1.**

- **phytoplankton (P)**
  - Grazing: \( R_m \cdot \Lambda \cdot P (1 - \exp(-\Lambda P)) \cdot Z \)
  - Death: \( m \cdot p \)
  - Photosynthesis: \( I_{\text{max}} \cdot \exp(-k \cdot Z) \times V_m \cdot N \cdot P / (K_s + N) \)
  - \( V_m = 2.0 \, \text{d}^{-1} \)
  - \( K_s = 0.1 \mu g \text{ at } N / \text{l} \)
  - \( k = 0.08 \, \text{m}^{-1} \)

- **zooplankton (Z)**
  - Unassimilated grazing fraction: \( \gamma \cdot R_m \cdot \Lambda \cdot P (1 - \exp(-\Lambda P)) \cdot Z - gZ \)
  - \( \gamma = 0.3 \)
  - Death: \( g = 0.2 \, \text{d}^{-1} \)
We assumed that the warm-core ring is axisymmetric like in FRANKS et al. (1986), and we took the value of the observed radial transact through the WCR 86B off Sanriku-area which showed that its radius was initially 150 km and its vertical structure extended up to 500 m depth. The initial conditions of physical parameters are in accordance with the WCR 86B except the vertical depth (the vertical depth is made rather shallower than that of WCR 86B because of the simplicity of calculation). Having assumed the initial density anomaly obtained by YASUDA et al. (1992), the velocity field is numerically calculated.

The model of the primary production dynamics is followed after FRANKS et al. (1986)’s to compare the results as shown in Fig. 2. In Case 1, the initial conditions are also taken to be the same as theirs. In Case 2, we modified the initial conditions to be horizontally uniform in order to consider the dependence of the results on the initial condition of nutrient.

The initial states of density anomaly (common in Cases 1 and 2) and NO$_3$-N (Case 1) across the WCR are shown in Fig. 3.

Results and discussions

Figure 4 shows streamlines of the horizontal flow field (which represents a barotropic mode of the horizontal current), the horizontal velocity field at 15 m level, and the horizontal distribution of vertical velocity at 25 m level 60 days after the initial state. Streamlines show an anticyclonic ring which corresponds to a WCR with spread four branches that are caused by possibly baroclinic instability. The vertical velocity field has a dipole-like structure which is explained in KISHI (1994). According to our model, the value of vertical velocity (maximum value is $5.1 \times 10^{-4}$ cm s$^{-1}$) is weaker than that of FRANKS et al. (1986) ($3 \times 10^{-3}$ cm s$^{-1}$) within the whole area in the WCR during its process of decay and this structure is considered to be an influence of the instability of the ring. This clearly differs from the zonal stream pattern of the model used by FRANKS et al. (1986) in which they supposed

![Fig. 3. (a) Initial density anomaly and (b) initial NO$_3$-N distribution across the WCR center.](image-url)
Fig. 4. (a) Streamlines of the horizontal flow field (contours are described $4.8 \times 10^9$ cm$^3$s$^{-1}$ interval and dashed lines indicate negative values), (b) horizontal velocity fields at 15 m level (maximum arrow shows 1.5 cm s$^{-1}$), and (c) horizontal distribution of vertical velocity at 25 m level (shaded portion indicates downwelling), on 60 days after the initial state.

Fig. 5. Case 1—Distribution across WCR of (a) $\text{NO}_3^-$-N, (b) phytoplankton-N, and (c) zooplankton-N, 60 days after the initial state (unit: $\mu$M).

upwelling at the center of the WCR and downwelling in its edge.

Figure 5 shows the distribution of $\text{NO}_3^-$-N, phytoplankton-N, and zooplankton-N in a zonal section. According to our results, the well known sub-surface chlorophyll maximum is also reproduced with the same biological parameters and initial conditions used by FRANKS et al. (1986). At first, uptake of $\text{NO}_3^-$-N by phytoplankton leads to surface deficiency of $\text{NO}_3^-$-N. Then the consumption of $\text{NO}_3^-$-N by uptake and supply of $\text{NO}_3^-$-N from deeper region by vertical diffusion are balanced around 150 m depth where the light intensity for uptake is small enough to balance with vertical diffusion of nutrient. The lens structure of phytoplankton at the center of the WCR that was formed in FRANKS et al. (1986)'s model was not appeared in our model, because the vertical supply of $\text{NO}_3^-$-N is not enough for the consumption by photosynthesis at the ring center.

On the other hand, in Fig. 6 which shows the distribution of $\text{NO}_3^-$-N, phytoplankton-N and zooplankton-N in a zonal section in Case 2, the subsurface chloro-
phyll maximum was also observed. But the characteristic structure of the WCR could not be reproduced. This fact shows that the initial field of NO$_3^-$-N which will be formed accompanied by the formation of the WCR is important to maintain the structure of ecological compartments at least for first two months from the beginning of WCR formation, and physical advection and diffusion has minor effect on the horizontal distributions of ecological compartments.

Although the observation of the surface temperature suggests that warm filaments from the Kuroshio were absorbed by the WCR 86B at about every 20 days interval (SUGIMOTO et al., 1992) accompanied by downwelling motion, our three dimensional model suggests the possibility of creating chl.a sub-surface maximum layer without such downwelling motion. This sub-surface chl.a maximum layer would be formed only by the balance of decrease of photosynthesis due to light attenuation and increase of it due to diffusion of nutrient.

PART 2—ECOSYSTEM MODEL IN SQUARE OCEAN
THAT SIMULATE NORTHERN PACIFIC

Model description

As a physical model, we used the same model as Part one.

The North Pacific model extends over a 3000 km square ocean with flat bottom, the depth of which is 3720 m, bounded all around by solid, no-slip walls. There are 11 vertical levels centered at 5, 15, 30, 55, 95, 170, 345, 595, 1220, 2220, 3220 m. The horizontal grid spacing is 75 km. The horizontal extent does not include the actual coastline, but it is enough to grasp the characteristics of the self-consistent ecosystem in this area. The eddy viscosities in the horizontal and vertical directions are $2.0 \times 10^7$ cm$^2$s$^{-1}$ and $10.0$ cm$^2$s$^{-1}$ respectively, while the eddy diffusivities in the two directions are $1.0 \times 10^7$ cm$^2$s$^{-1}$ and $1.0$ cm$^2$s$^{-1}$ respectively. We considered only wind driven circulation for the simplicity. The constant zonal wind stress with sine structure is given which forms as stream lines shown in Fig. 7 (1 year after the initial state). Having assumed the initial density anomaly horizontally constant, the velocity field is zero. The model of the primary production dynamics is considered
Fig. 7. Streamlines of the horizontal flow field of Part 2 (contours are described $9.2 \times 10^{12}$ cm$^3$s$^{-1}$ interval and dashed lines indicate negative values).

Chl.a / N = 1.0 (mg chl.a m$^{-3}$/μ M N)

photosynthesis

$\frac{I}{V_m \cdot N \cdot P / (K_s + N)}$

phytoplankton (P)

grazing

$R_m \cdot \Lambda \cdot P (1 - \exp(-AP)) \cdot Z$

$\Lambda = 1.0 (mg \ chl.a \ m^{-1})$

$m = 0.25 \ d^{-1}$

death

m-p

m = 0.1 d$^{-1}$

decomposition

0.921 d$^{-1}$

zooplankton (Z)

unassimilated

grazing fraction

$\gamma \cdot R_m \cdot \Lambda \cdot P (1 - \exp(-AP)) \cdot Z - gZ$

$\gamma = 0.5 \ \Lambda = 1.0 (mg chl.a \ m^{-3})$

$g = 0.1 \ d^{-1}$

dead

PON + DON

sinking

140 m d$^{-1}$

Fig. 8. Conceptual diagram of ecosystem model of Part 2.
to describe simple production mechanism with four compartments (constituents) i.e., a famous so called NPZD model shown in Fig. 8. The values of biological parameters are different from those of Case one. Because in Case one, the main purpose of our study is to compare the results with the former research, however in Case two we used the value obtained in NOPACCS (Northwest Pacific Carbon Cycle Study) project carried out by NEDO (New Energy Development Organization, Ministry of Trade and Industry).

Results and discussions

Figures 9 show longitudinal sections along middle longitude of upper 350 m after 1 year from the initial state. As the thermal effect is not included the thermocline and nutricline will weaken in time. The results 1 year after the initial state are almost just after the nutricline is formed and the ecosystem at surface layer shows steady state feature.

As to the surface PON + DON maximum near the north equatorial front, this was formed by dead phytoplankton which is supplied by high phytoplankton

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Fig. 9. Distribution of (a) chl.a (unit: mg chl.a m\(^{-3}\)), (b) NO\(_3^-\)-N (unit: \(\mu\)M), (c) zooplankton (unit: \(\mu\)M), and (d) PON + DON (unit: \(\mu\)M), 360 days after the initial state across S-N section at the center of the model region. The horizontal scale of the model is 3000 km × 3000 km, however within this scale the subarctic and subtropical gyres are included, the indications of latitude of the figure are written in this sense.
concentration due to nutrient supply by the upwelling along the front and also suitable light intensity. On the other hand the surface PON + DON maximum at the center of subarctic gyre is also formed by high primary production based on the nutrient supply through the upwelling due to wind curl.

If we set a PON collector at 350 m depth in the center of subarctic gyre in the model ocean 22 mgN m$^{-2}$d$^{-1}$ (if we use C/N = 133/17 as shown in Part 3, this value is converted to 172 mgC d$^{-1}$) of PON will be accumulated. This value does not differ so much from NÔRIKI and TSUNOGAI (1986) and BERGER (1989)’s results. The horizontal scale of the model is half or one third of the Pacific, however the transport of western boundary current is about 52 Sv. This means wind curl of the model is much larger than the real Pacific and upwelling in subarctic gyre is also large. This may cause the different behavior of sinking particles from realistic ocean model.

Although the model shown here is a preliminary one without any heating/cooling or precipitation, we could grasp the characteristics of four compartment model (i.e., what is called PZDN model). We suggest it would be a better selection to divide POM and DOM to discuss the POM sinking ratio and F ratio in the ocean than PZDN model.

PART 3—ONE DIMENSIONAL ECOSYSTEM MODEL THAT IS APPLIED TO STATION PAPA

There exist some vertical one-dimensional models coupled with mixed layer models e.g., VARELA et al. (1992), WROBLEWSKI and RICHMAN (1987), AKSNES and LIE (1990), RADACH and MOLL (1993). VARELA et al. (1992) have investigated the factors which contributes the formation of the deep chlorophyll maximum, and WROBLEWSKI and RICHMAN (1987) studied the effects of episodic wind mixing. The purposes of these two are rather different from our study. AKSNES and LIE (1990) and RADACH and MOLL (1993) intended to reproduce time variation of particular regions and utilized observational information for grazing pressure. Their models are not self-consistent because some biological activities are assimilated to the observation. Our study gives footlights on the self-consistent ecosystem model in a particular region which may enable to extend to global scale.

Model description

We consider seven compartments as constituents of the ecosystem. Time evolution of those constituents are described with differential equations like Part one and two except horizontal diffusion or advection terms. The vertical diffusion coefficients are calculated with a level 2 closure model (not constant like Part one or two) after MELLOR and DURBAN (1975). We have constructed a nitrogen based model composed of phytoplankton (Chl), zooplankton (Zoo), nitrate (NO$_3$), Ammonia (NH$_4$), particulated organic nitrogen (PON), dissolved organic nitrogen (DON) and dissolved oxygen (DO). In the parentheses are their mathematical symbols and also as for particulated organic nitrogen and dissolved organic nitrogen we will use PON and DON respectively in the text. Nitrogen based material flows are shown in Fig. 10.
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Fig. 10. Conceptual diagram of ecosystem model of Part 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{max}$</td>
<td>Maximum Photosynthetic Rate at 0°C</td>
<td>1.000 /day</td>
</tr>
<tr>
<td>$k$</td>
<td>Temperature Coefficient for Photosynthetic Rate</td>
<td>0.063 /°C</td>
</tr>
<tr>
<td>$K_N$</td>
<td>Half Saturation Coefficient for Inorganic Nitrogen</td>
<td>3.0 μmol/l</td>
</tr>
<tr>
<td>$I_{opt}$</td>
<td>Optimum Light Intensity</td>
<td>0.07 lq/min</td>
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<tr>
<td>$q_1$</td>
<td>Light Dissipation Coefficient of Sea Water</td>
<td>0.035 /m</td>
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<tr>
<td>$q_2$</td>
<td>Self Shading Coefficient</td>
<td>0.0281 lq/μmol N m</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Ammonium Inhibition Coefficient</td>
<td>1.5 lq/μmol</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of Extracellular Excretion to Photosynthesis</td>
<td>0.135</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Respiration Rate at 0°C</td>
<td>0.03 /day</td>
</tr>
<tr>
<td>$k_R$</td>
<td>Temperature Coefficient for Respiration</td>
<td>0.0519 /°C</td>
</tr>
<tr>
<td>$M_{P0}$</td>
<td>Phytoplankton Mortality Rate at 0°C</td>
<td>0.0281 lq/μmol N day</td>
</tr>
<tr>
<td>$k_{MP}$</td>
<td>Temperature Coefficient for Phytoplankton Mortality</td>
<td>0.069 /°C</td>
</tr>
<tr>
<td>$GR_{max}$</td>
<td>Maximum Grazing Rate at 0°C</td>
<td>0.30 /day</td>
</tr>
<tr>
<td>$k_g$</td>
<td>Temperature Coefficient for Grazing</td>
<td>0.0693 /°C</td>
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<tr>
<td>$\lambda$</td>
<td>Ilev Constant</td>
<td>1.4 lq/μmol N</td>
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<td>$Chl^*$</td>
<td>Threshold Value for Grazing</td>
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<tr>
<td>$\alpha$</td>
<td>Assimilation Efficiency of Zooplankton</td>
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<td>$\beta$</td>
<td>Growth Efficiency of Zooplankton</td>
<td>0.30</td>
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<td>$M_{Z0}$</td>
<td>Zooplankton Mortality Rate at 0°C</td>
<td>0.0585 lq/μmol N day</td>
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<tr>
<td>$k_{MZ}$</td>
<td>Temperature Coefficient for Zooplankton Mortality</td>
<td>0.0693 /°C</td>
</tr>
<tr>
<td>$V_{P10}$</td>
<td>PON Decomposition Rate at 0°C (to Inorganic Nitrogen)</td>
<td>0.030 /day</td>
</tr>
<tr>
<td>$V_{PIT}$</td>
<td>Temperature Coefficient for PON Decomposition (to Inorganic Nitrogen)</td>
<td>0.0693 /°C</td>
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<tr>
<td>$V_{P10}$</td>
<td>PON Decomposition Rate at 0°C (to DON)</td>
<td>0.030 /day</td>
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<td>$V_{PDT}$</td>
<td>Temperature Coefficient for PON Decomposition (to DON)</td>
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<td>$V_{D10}$</td>
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<td>$V_{DIT}$</td>
<td>Temperature Coefficient for DON Decomposition</td>
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<tr>
<td>$k_{N0}$</td>
<td>Nitrification Rate at 0°C</td>
<td>0.030 /day</td>
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<tr>
<td>$k_{NT}$</td>
<td>Temperature Coefficient for Nitrification</td>
<td>0.0693 /°C</td>
</tr>
<tr>
<td>$W$</td>
<td>Vertical Current Velocity</td>
<td>0.36 m/yr</td>
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Table 2. Boundary conditions at the bottom of the model (Part 3). The value for nitrate is taken from Levitus et al. (1993) and that of dissolved oxygen is from Miller et al. (1984)

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phytoplankton</td>
<td>0 μmolN/l</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>0 μmolN/l</td>
</tr>
<tr>
<td>Ammonium</td>
<td>0 μmol/l</td>
</tr>
<tr>
<td>Nitrate</td>
<td>37 μmol/l</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>100 μmol/l</td>
</tr>
</tbody>
</table>

To calculate time dependent features of the compartments, all the processes described in Fig. 10 must be formulated and detailed descriptions are shown in Kawamiya et al. (1995) (see Table 1).

The physical model to calculate vertical diffusion coefficients is after Mellor and Durban (1975) i.e., 2 level model. There are 28 layers in the domain. The upper 100 m was divided into 20 layers whose thicknesses are 5 m, and the rest was divided into eight layers whose thicknesses are 10 m, 10 m, 10 m, 20 m, 30 m, 60 m respectively. For the compartments other than phytoplankton and zooplankton, homogeneous values equal to those at the bottom (Table 2) are given throughout the domain as the initial values. As for phytoplankton and zooplankton, 0.16 μM and 0.38 μM respectively for the upper 120 m and 0 μM for below 120 m. The initial vertical distributions of temperature and salinity are taken from averaged vertical profile based on the observed data in 1980.

At the surface, temperatures and salinities were fixed to the observational values obtained in 1980, dissolved oxygen was set to be equal to saturation concentration which was calculated from temperature and salinity with the equation proposed by Weiss (1970), and other compartments were set no exchange between atmosphere and ocean. For calculating wind stress from wind data at surface, ECMWF objective analysis data at the location of Station Papa were used. For the bulk coefficient, Wyrtki and Meyers (1976)'s formula was adopted. At the bottom of the model, temperature and salinity were fixed to 4.5°C and 33.91 psu respectively, no exchange of momentum was allowed across the bottom, no vertical gradient condition is assumed for PON and DON, and other compartments are fixed at the bottom shown in Table 2. In order to get the steady cycle features the biological model was integrated for 101 years with the time step 0.1 day and results obtained during last one year were picked up.

Results and discussions

Figure 11 shows the time dependent features of the vertical profile of (a) calculated temperature and (b) observed one. The profile coincides each other. Our physical model could reproduce the physical field.

Figure 12 shows the time dependent features of each compartment. Phytoplankton concentration is converted to chl.a using C:N = 133:17 and C:chl.a = 50:1 (from Strickland, 1965). Figure 13 shows a time dependent vertical profile of observed chl.a obtained by Clemons and Miller (1984). The chlorophyll maximum which
appears in March was reproduced by the model though it is more intensive. This maximum is strongly associated with the seasonal variation of vertical diffusion coefficient. Figure 14 shows the time dependent feature of vertical diffusion coefficient. The shaded portion represents the area where its value is more than 10 cm$^2$s$^{-1}$. Phytoplankton concentration increases as the shaded area retreats in February and decreases as the shaded area deepens at the beginning of April. This is because when diffusivity is large, each individual of phytoplankton cannot stay long enough at the surface where light environment is suitable, and *vice versa*. The model cannot reproduce the maximum that appears from fall to winter in Fig. 13. Fall phytoplankton maxima are often related to enhanced vertical mixing and following increase of nutrient concentration. However, at Station Papa, nutrient concentration is always high (more than 10 $\mu$M) compared to observed half saturation constant. Thus, the contribution of enhanced mixing to phytoplankton growth cannot be so
Fig. 12. Time dependent vertical structure calculated by our model. (a) Nitrate, (b) Ammonium, (c) phytoplankton, (d) Zooplankton, (e) PON, (f) DON, and (g) Dissolved oxygen.
Fig. 12. (continued).
large as to form the maximum. The possible reasons for the discrepancy are (1) dominant species change in fall (CLEMONS and MILLER, 1984) and photosynthetic rate is still around maximum in October while decreased solar radiation is not enough for maximum photosynthesis in our model (2) dominant net zooplankton species leave from surface into the deeper region at the end of August to prepare for spawning (MILLER et al., 1984), while our model does not include a life history of zooplankton. Figure 15 represents the observed annual nitrate variation at Station Papa by CLEMONS and MILLER (1984). The results of the model (Fig. 12(a)) could reproduce this overall feature although it does not show the minimum in fall associated with the phytoplankton maximum. described above. The ammonium inhibition only slightly contributes for maintaining the high nitrate concentration. The detailed discussions
Fig. 14. Time dependent vertical structure of diffusion coefficient. The shaded portion represents the large diffusivity (more than 10 cm²s⁻¹) areas.

Fig. 15. Time dependent vertical structure of observed nitrate, redrawn from Clemons and Miller (1984) (unit: µM).

are shown in Kawamiya et al. (1995).

For the yearly production, 50 gC m⁻²y⁻¹ was obtained by the model. This value is close to Berger (1989)'s estimation (60 gC m⁻²y⁻¹) at Station Papa, but rather smaller than the value (170 gC m⁻²y⁻¹) by Welschmeyer et al. (1993) obtained at Station Papa in the SUPER Project. The absence of the fall maximum in our model is possible cause for the difference between the model and their estimation.

Acknowledgements—The authors are grateful to Professor N. Suginohara and Dr. Y. Yamanaka of CCSR of University of Tokyo, Professor A. Masuda of Kyushu University, Dr. A. Yoshimori of Nagoya University and Dr. I. Yasuda of Hokkaido University for their useful discussions. And we also thank Dr. Matsuyama and Dr. Oki for providing ECMWF data.

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