Obtaining Reasonable Results in Different Oceanic Regimes with the Same Ecological-Physical Coupled Model

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A vertically one-dimensional, ecological-physical coupled model is applied to the Bermuda Atlantic Time-series Study (BATS) site and Ocean Weather Station Papa. These sites have quite different oceanographic characteristics because the former is located in an oligotrophic, subtropical region while the latter is in a eutrophic, subpolar region. With changes in only a few parameters, the model can reproduce the contrast between the sites that nitrate is far more abundant at Papa than at the BATS site, while chlorophyll abundance and primary production are only moderately higher at the former. The parameter changes are justifiable on the basis of observational data.

Keywords:
- Ecological model
- BATS
- PAPA
- mixed layer model

1. Introduction

Primary production and subsequent associated processes occurring at the ocean surface play a key role of biogeochemical cycling. Numerical models, together with observations, can serve to help in understanding such behavior. Indeed, many studies have been carried out on the role of the surface biota using numerical models, most of which are on a much smaller scale than global (e.g., Fasham et al., 1990; Radach and Moll, 1993; Doney et al., 1996). Recently, however, the model of Fasham et al. (1990) was coupled with an oceanic general circulation model (OGCM) to simulate basin scale behavior of the surface biota in the Atlantic (Fasham et al., 1993; Sarmiento et al., 1993). Before one entertains such a coupling, one obviously needs to verify the model using observational data at some particular sites. Fasham et al. (1990) and Fasham (1993) showed that the model produces fairly good results when compared with data from Hydrostation S (64°W, 32°N) and from Ocean Weather Station (OWS) India (19°W, 59°N), respectively. It is very logical to choose those sites for testing a model because the two sites lie in completely different oceanic regimes from each other, as is easily seen, for instance, in Levitus et al. (1993).

Furthermore, Fasham (1995) explored the causes for the difference in seasonal variation between the North Atlantic and the North Pacific using a box model. By changing only physical conditions, i.e., mixed layer depth (MLD) and solar radiation, the distinct contrast between these area could be successfully reproduced. The conclusion basically supports the notion of Evans and Parslow (1985) that the shallow winter mixed layer in the North Pacific prevents a bloom by maintaining sufficient herbivore biomass to suppress it. The studies referred to above proved that, at least within the scope of box models, a single ecosystem model can be applied to various sites if one takes sufficient care over such external conditions as MLD and light intensity. A following step will be to see whether or not success can be achieved with a more complex model in which values prescribed in the above-mentioned models are determined internally.

A vertically one-dimensional, ecological-physical coupled model developed by Kawamiya et al. (1995) (henceforth KKYS), which is also intended to be coupled with an OGCM, has been calibrated with data obtained at OWS Papa (145°W, 50°N). In this model, MLD and nutrient concentration at the bottom of the mixed layer are obtained as model outputs, in contrast to Fasham et al. (1990), Fasham (1993), and Fasham (1995), where they are given as model inputs. Both quantities are important for determining biological activities in the ocean surface. In particular, biological activity is governed by both physical and biological processes. Therefore it is still meaningful to see whether acceptable results can be obtained at different sites with this model.

Here we present the results obtained by applying the model to the Bermuda Atlantic Time-series Study (BATS) site, near Hydrostaion S (cf., Michaels and Knap, 1996). In this case, too, the oceanic regimes where those sites are located differ greatly from each other. Namely, concentrations of nutrients are far higher in the former, while chlorophyll concentration and primary production are of the same order. This distinct contrast will enable us to conduct an effective test of our model.
We also show the results for OWS Papa since some modifications have been made to the KKYS model. By comparing the results obtained from the BATS site and OWS Papa, we intend to examine the model’s capability to reproduce the differences as well as similarities in the ecosystem dynamics between these sites.

2. Simulation of the BATS Site

Here we describe the structure and the settings of the model for the BATS site. Some modifications made for the re-examination of OWS Papa will be described later.

2.1 Model description

Two sub-models are needed for this study, one of which is a mixed layer model and the other an ecological one.

The mixed layer model adopted here is the Mellor and Yamada (1982) level 2.5 scheme as improved by Kantha and Clayson (1994), rather than the level 2 scheme used by KKYS. This model partly, if not completely, overcomes the deficiency of the closure schemes that the development of a mixed layer cannot penetrate deeply enough (e.g., Martin, 1985).

The ecological model is basically the same as the one developed by KKYS. Figure 1* shows its structure. Those points that have been changed from the original model are as follows:

- The seasonal variation of day length have been incorporated;
- Different values have been assigned to the half saturation constants for nitrate and ammonium (the values are given in Table 1);
- Values of some parameters have been slightly changed as shown in Table 1.

Among the parameters changed, the half saturation constant for nitrate has been changed rather dramatically by two orders of magnitude. This change can be justified because the model is now applied to an oligotrophic region, unlike in

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*Fig. 1. Structure of the ecological model. Boxes represent nitrogen based standing stocks and arrows represent nitrogen flows in the ecosystem. Dashed arrows represent the exchange through diffusion and advection.
KKYS where the simulation was performed for a eutrophic region, viz., OWS Papa. This constant is known to be far smaller in oligotrophic than in eutrophic regions (e.g., Parsons et al., 1984; Harrison et al., 1996).

2.2 Boundary and initial conditions

The maximum depth of the domain and grid intervals are identical to those in KKYS. The domain extends to a depth of 330 m and it is divided into 28 layers; the grid intervals are 5 m in the upper 100 m then gradually get larger with depth to 60 m in the bottom layer. Boundary conditions are set in almost the same way as in KKYS for both the mixed layer model and the ecological model, except that the data are taken from the BATS site. That is, temperatures and salinities at the sea surface are fixed to the time-dependent observational values and those at the bottom of the domain are fixed to constant values.

For the vertical profile and the temporal variation of vertical current velocity which must be specified, we followed Musgrave et al. (1988) who modeled its seasonal cycle by a cosine curve. Furthermore, we use a rather large value of 1.0 cm²s⁻¹ for background vertical diffusivity and viscosity, as was adopted by Doney et al. (1996). Musgrave et al. (1988) argued that this large value is necessary to simulate the seasonal cycle of the upper ocean near Bermuda.

Model integrations have been done for the years 1989 to 1992. For the mixed layer model, initial conditions for temperature and salinity profiles are taken from the BATS data. For initial conditions of the ecological model, we used the profiles of January 1 picked up from the steady cycle obtained by the model under the forcing of the year 1989.

2.3 Results

Figures 2 and 3 show “climatological” seasonal variations of chlorophyll and nitrate at the BATS site as produced by the model together with observational data (Doney et al., 1996). An N/Chlorophyll a (N/Chl) ratio of 7.5 was used based on a C/N ratio of 7.8 (Takahashi et al.,...
1985) and a common C/Chlorophyll \( a \) ratio of 50. Some characteristic features seen in the observational figure are well reproduced by the model, viz.: high abundance of chlorophyll in winter season throughout the water column, deep chlorophyll maximum in summer at the depth of nitracline, and nitrate depletion in the surface layer.

Modeled annual primary production averaged over the four years is 98 gC m\(^{-2}\) yr\(^{-1}\), using a C/N ratio of 7.8. This is in good agreement with the estimate of 110–140 gC m\(^{-2}\) yr\(^{-1}\) given by Lohrenz et al. (1992). However, this match is fortuitous rather than illustrative of the model’s capability to reproduce the dynamics of the surface ecosystem. Most vigorous production occurs in the model at the bottom of the euphotic zone in summer (Fig. 4), while the observations show that primary production is higher in the upper portion of the euphotic zone, especially from February to March (Lohrenz et al., 1992; Doney et al., 1996). The Doney et al. (1996) model also suffers from a similar discrepancy and gives some possible explanations, namely: nitrogen fixation in the upper euphotic zone, shift of community structure between the upper and the lower euphotic zone, and variation of C/N ratio.

The ratio of annual export of nitrogen across 150 m to the total annual primary production, which is equivalent to the f-ratio in a steady state, is 5.9\%. This is within the range of the estimate of 5–7\% given by Michaels and Knap (1996).

The modeled trend of decreasing chlorophyll concentration to the surface is not strong enough compared with the observational data (Fig. 2). The extremely low chlorophyll concentration in the uppermost layer of the subtropical regions is believed to be a result of increase of N/Chl ratio due to photoadaptation (Winn et al., 1996), rather than a result of the decrease of biomass itself. This adaptation may have some relation with the high surface production mentioned above. But the Doney et al. (1996) model, which incorporates the variation of N/Chl ratio, has not succeeded in reproducing it, either.

3. Re-Examination of OWS Papa

After KKYS, the model has been slightly modified, as stated in Section 2, and some parameter values have been changed in order to obtain good results for both the BATS site and OWS Papa with the least number of different parameters between the two locations. Thus, it is appropriate to publish the results of our re-examination of OWS Papa, even though those of our first simulation of OWS Papa were described in KKYS.

In our re-examination we retained most parameters at the same to values as those for the BATS site simulation. Moreover, boundary and initial conditions are set in almost the same way as for the BATS site. Some points that should be mentioned are the following:

- vertical current velocity is modeled using the cosine function and Hellerman and Rosenstein (1983)’s wind stress data in a similar way as was adopted for the BATS site simulation, in contrast to KKYS, where it is neglected;
- background diffusivity and viscosity are set to 0.3 cm\(^{2}\) s\(^{-1}\) as in KKYS.
some parameter values are changed from those for the BATS site simulation as specified in Table 1. Changes of order(s) of magnitude in the half-saturation constants for nitrate and ammonium are justifiable, as is explained in Section 2. The larger sinking velocity of particulate organic nitrogen (PON) in OWS Papa is also qualitatively valid due to of the fact that subpolar regions are dominated by relatively large phytoplankton compared with subtropical regions (e.g., Ishizaka et al., 1994).

During the course of re-examination, we found an unrealistic setting in the KKYS calculation (see Appendix). Re-examination was conducted after fixing the setting and the results for chlorophyll concentration and nitrate are displayed in Figs. 5 and 6, respectively. KKYS have corresponding observational figures, their Figs. 7 and 11*, which can be compared with those figures. As was noted in KKYS, the model can reproduce the chlorophyll maximum in March resulting from the retreat of the mixed layer due to the weakening of wind, while it does not show the fall maximum, the cause(s) of which may be the life history of zooplankton and/or the succession of phytoplankton species; on the other hand, it can successfully reproduce the maintenance of the high nutrient concentration compared to that in the subtropical oligotrophic regions. Annual primary production obtained by the model is 122 gC m$^{-2}$yr$^{-1}$, 29% of which is exported across 100 m depth. This production rate has increased rather drastically from 50 gC m$^{-2}$yr$^{-1}$ calculated by KKYS, due mainly to the recalibration of the setting. The newly calculated production roughly agrees with the estimate of 140 gC m$^{-2}$yr$^{-1}$ given by Wong et al. (1997). Furthermore, the ratio of the export production to the primary production is higher at OWS Papa than at the BATS site; this result also agrees with the observational fact that the ratio tends to be smaller value is then taken as the uptake by photosynthesis. This is mathematically formulated as below;

$$(\text{Production}) = \min \left\{ \frac{\text{PO}_4}{K_{\text{PO}_4} + \text{PO}_4}, \frac{\text{NO}_3}{K_{\text{NO}_3} + \text{NO}_3} \exp(-\Psi \text{NH}_4), \frac{\text{NH}_4}{K_{\text{NH}_4} + \text{NH}_4} \right\} 	imes (\text{terms describing the dependencies on temperature, light, and chlorophyll a})$$

where $\text{PO}_4$ is phosphate concentration, $\text{NO}_3$ nitrate, $\text{NH}_4$ ammonium, $\Psi$ the ammonium inhibition coefficient, and $K_i$ the half-saturation constant, while the subscript $i$ represents value of $\text{PO}_4$, $\text{NO}_3$, and $\text{NH}_4$, $\min(a, b)$ equals the smaller one of $a$ and $b$.

In KKYS, we set the values of the half-saturation constant and the bottom concentration for phosphate which we thought, respectively, small and large enough to prevent phosphate from becoming the limiting nutrient. During the calculations, however, phosphate became the limiting nutrient rather than nitrate and ammonium due to the highly nonlinear uptake of nitrogen. We did not notice this and continued to analyze the results by focusing on nitrate as the limiting nutrient.

References


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