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Coupling of Physical and Bio-Geochemical Process and Monitoring Ocean Circulation Using Data Assimilation System

Y. Ishikawa[1]*, T. Awaji[1], M. Ikeda[2] and T. Toyoda[3]

[1]*Graduate School of Science, Kyoto University,*
Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-9502, Japan
[2]*Graduate School of Environmental Science, Hokkaido University,*
N10W5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan
[3]*Meteorological Research Institute, Japan Meteorological Agency,*
1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan
**E-mail: ishikawa@kugi.kyoto-u.ac.jp*

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Introduction

Since the distribution of oceanic biogeochemical tracers, and their variabilities, are strongly controlled by the physical environment, such as velocities, temperature, and mixing strength, monitoring of the 4-dimensional structure of the circulation field is of importance for understanding the mechanism of the ocean ecosystem. In particular, many studies have reported that active biological processes appear around the meso-scale eddies associated with upwelling and/or the horizontal advection of nutrients. For this purpose, a data assimilation system is a very powerful tool, because it can provide a realistic dataset whilst conserving physical consistency. In this study, we have developed a data assimilation system for the oceanic biogeochemical circulation, as well as the physical environmental field.

Estimation of Subsurface Carbon Distribution

The Subarctic region in the North Pacific is a region of high activity of the ocean ecosystem, so an estimation of the amount of CO_2 absorption is very important. It is well known that CO_2 is absorbed in spring and summer because of active blooming; however, CO_2 is released from ocean in the winter because a deepening of the mixed layer lead the entrainment of CO_2 rich water in subsurface layer into the surface layer. To estimate the amount of winter emission, the CO_2 distribution of the subsurface layer is necessary through the entrainment process.

The data assimilation system is constructed to estimate the subsurface CO_2 distribution using an adjoint method. As observation data, surface CO_2 pressure data and carbonate is assimilated into a simple ocean model, which includes mixed

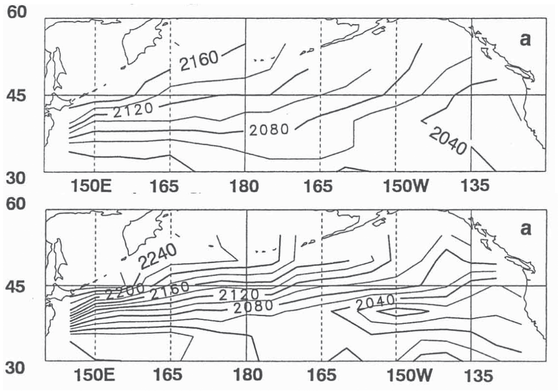

Fig. 1. Distribution of DIC at 100 m depth. (Upper) Without assimilation. (Lower) Estimation by assimilation system.

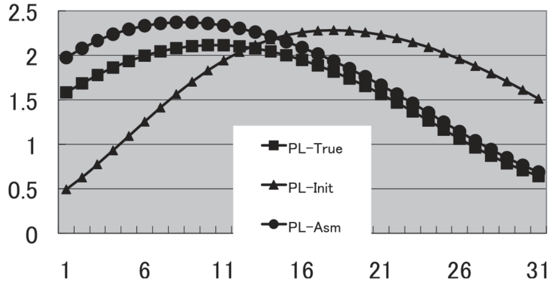

Fig. 2. Time series of the large phytoplankton (PL) for true field (square), initial guess (triangle), and assimilation result (circle).

layer processes. For a first guess, we use the result derived by Ikeda and Sasai (2000), in which the subsurface CO_2 field is estimated from the surface CO_2 distribution, by adding a constant value.

Figure 1 shows the result of the estimated distribution using the data assimilation system with the first guess field. The difference between these results is remarkable especially in the Kuroshio extension, and mixed water regions, and as a result of the assimilation, the estimated surface CO_2 pressure is changed by about 50 ppm. This is because that the advection effect of the strong Kuroshio extension current is accounted for in the assimilation result. The advection by the Kuroshio current affects the subsurface CO_2 field through the following two ways; one is the direct effect of the advection of CO_2 as a passive tracer, and the other is the deepening of the mixed layer around the Kuroshio extension region by advecting the warm Kuroshio water into the subarctic region. In the latter process, the effect of the meso-scale variability plays an important role, so that it is necessary to reconstruct a realistic meso-scale feature of a coupled physical and bio-geochemical field.

State Estimation Method for Ocean Ecosystem Model

The data assimilation experiment for

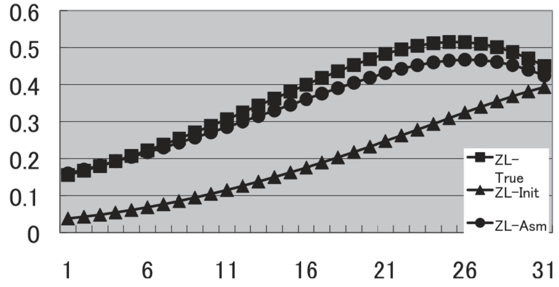

Fig. 3. Same as Fig. 2, but for large zooplankton (ZL).

Table 1. The RMS error of each variable for simulation (initial guess) and assimilation (10^{-2} μmolN/l).

	PS	PL	ZS	ZL	ZP	NO_3	NH_4	PON	DON	$SiOH_4$	Opal
Sim	19.9	70.6	1.64	18.6	1.69	63.0	11.6	5.87	31.3	114.2	16.2
Asm	21.8	21.7	0.67	3.46	1.59	19.0	8.9	1.73	20.0	195.1	5.8

the ocean ecosystem model has developed rapidly recently and many studies have focused on climatological seasonal fields, as shown in the previous section, to estimate the unknown parameters in the ecosystem model. However, the interannual variability of the ocean ecosystem is very important and needs to be represented by the assimilation system. For this purpose, the state estimation of the bio-geochemical field is necessary, in addition to the parameter estimation. In this study, a data assimilation system for a simple ecosystem model is constructed to show the ability for the state estimation of the bio-geochemical field. To examine the ability of the data assimilation system, an identical twin experiment is a useful tool, in which the true field is derived by a model simulation and observation data is sampled from the true field. Since the true field is fully known and it is not necessary to consider the model deficiency, we can evaluate the efficiency of the assimilation system directly.

The oceanic ecosystem model used for the data assimilation is the 1-box version of the NEMURO model (Kishi *et al.* 2007), which is 11 compartment lower trophic model developed to represent the realistic ecosystem in the North Pacific. The data assimilation system is constructed using an adjoint method, in which the NEMURO model is used as a strong constraint, and the initial conditions of the model are estimated as the control variables.

Before the experiment, a 4-year spin-up is carried out using the parameters selected for station A7 (Kishi *et al.* 2007; Yoshie *et al.* 2007). After the spin-up, a 1-month result in May is selected as the true field. The total amount of the phytoplankton (small + large phytoplankton: PS+PL), for every 3 days is sampled from the true field as the observation data, and no observation data is added to the observation data to simplify the experimental setting. For the initial guess of the experiment, the bio-geochemical field on April 1st is used for the initial condition of the model, which should be corrected by assimilating the observation data. It should be noted that the physical environment, such as tempera-

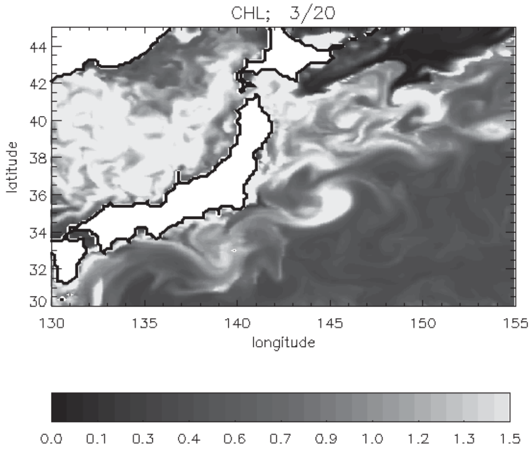

Fig. 4. Distribution of the Chl-a derived from the coupled physical and bio-geochemical model with eddy resolving.

ture, mixed layer depth, and forcing parameters.

Figure 2 shows the time series of the large phytoplankton (PL) for the true field, the initial guess field, and assimilation result, respectively. In this figure, it is clearly shown that the assimilation system can correct the strength and period of the spring blooming, while the peak of the blooming appears half a month later in the initial guess field. The correction in the assimilation field is due to the correction of the initial condition of the large phytoplankton (PL) itself. However, this correction of the initial condition cannot explain the decrease of PL in the latter half of the assimilation period. The decrease of PL after day 10 is controlled by the predation of the large zooplankton (ZL). As shown in Fig. 3, the estimated ZL is increased compared to the initial guess by the correction of the initial condition of ZL. It should be noted that ZL is not assimilated directly into the model, so that the observation data of phytoplankton can correct the initial condition of ZL through the assimilation process. This means that the observation data can correct not only the observed variable directly but also the whole model fields. This is the major advantage of the adjoint method, which is well known for the assimilation system for the physical model, and is also applicable for the ecosystem model.

To evaluate the efficiency of the assimilation system quantitatively, RMS differences with the time series of the true run are summarized in Table 1 for the initial guess and assimilation, respectively. Some variables, such as PL, ZL, NO_3 show a significant reduction of RMS errors. These variables show a large variability in time and large errors in the simulation run, so that the assimilation system can represent the major feature of the spring blooming in the true field using the observation data of phytoplankton PS+PL.

As shown in this section, state estimation of ocean bio-geochemical field is attained from a realistic amount of observation data, although the assimilation system is rather simple and the experimental design is idealized. In addition, since a strong constraint of the numerical model is adopted in the adjoint method, the time series of the assimilation result satisfies the governing model equation. This is a big advantage of the adjoint method, because there are no artificial sink/source of tracers during the assimilation period. In this experiment, the total amount of nitrogen is conserved through the assimilation period, so that the derived dataset from the assimilation is useful for clarifying the bio-geochemical processes in the ocean.

Conclusions

The data assimilation system is a powerful tool to investigate the ocean bio-geochemical processes, as shown in the previous sections, and will be developed further in the near future. As shown in the second section, meso-scale eddies play an important role in the bio-geochemical processes in the North Pacific, especially in the Kuroshio extension region. We are now developing a coupled physical and bio-geochemical model with resolving meso-scale variablities. Figure 4 shows the sample of the model result in the Kuroshio extension region. In Fig. 4, the physical circulation field is derived by the data assimilation system with an eddy-resolving model (Ishikawa *et al*. 2009), and the ocean ecosystem model NEMURO is embedded into the ocean general circulation model.

It is clearly shown that the spatial distribution of Chl-a strongly depends on the meso-scale eddies in the Kuroshio extension, and mixed water regions. We will develop the data assimilation system using this coupled physical and bio-geochemical model with adjoint method described in third section. The data assimilation system with an eddy-resolving coupled model can provide realistic features of the oceanic bio-geochemical circulation and its variability so that the analysis of the reanalysis data set derived from such a data assimilation system will contribute to clarifying the oceanic bio-geochemical processes. The data assimilation system for state estimation can provide the initial conditions of the numerical prediction, and the predictability of the bio-geochemical circulation will be examined using this system. Moreover, the advanced technique has been applied to estimate the parameters in an ecosystem model (Toyoda *et al*. 2011). In their study, the global ocean is divided into 40 regions and 32 parameters are estimated in each region to derive not only the realistic seasonal cycle, but also the inter-annual variability of the bio-geochemical circulation. The combination of such advanced parameter estimation and stated estimation is necessary to obtain a more realistic circulation of the physical and bio-geochemical field.

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