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 CO2 absorption is very important. It is well known that CO2 is absorbed in spring and summer because of active blooming; however, CO2 is released from ocean in the winter because a deepening of the mixed layer lead the entrainment of CO2 rich water in subsurface layer into the surface layer. To estimate the amount of winter emission, the CO2 distribution of the subsurface layer is necessary through the entrainment process.

The data assimilation system is constructed to estimate the subsurface CO2 distribution using an adjoint method. As observation data, surface CO2 pressure data and carbonate is assimilated into a simple ocean model, which includes mixed

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

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Introduction

Since the distribution of oceanic bio-geochemical 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 bio-geochemical circulation, as well as the physical environmental field.

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The data assimilation system is constructed to estimate the subsurface CO2 distribution using an adjoint method. As observation data, surface CO2 pressure data and carbonate is assimilated into a simple ocean model, which includes mixed
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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
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.

Table 1. The RMS error of each variable for simulation (initial guess) and assimilation ($10^{-2}$ $\mu$molN/$L$).

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>PL</th>
<th>ZS</th>
<th>ZL</th>
<th>ZP</th>
<th>NO$_3$</th>
<th>NH$_4$</th>
<th>PON</th>
<th>DON</th>
<th>SiOH$_4$</th>
<th>Opal</th>
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<tr>
<td>Sim</td>
<td>19.9</td>
<td>70.6</td>
<td>1.64</td>
<td>18.6</td>
<td>1.69</td>
<td>63.0</td>
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<td>5.87</td>
<td>31.3</td>
<td>114.2</td>
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<tr>
<td>Asm</td>
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<td>21.7</td>
<td>0.67</td>
<td>3.46</td>
<td>1.59</td>
<td>19.0</td>
<td>8.9</td>
<td>1.73</td>
<td>20.0</td>
<td>195.1</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Fig. 3. Same as Fig. 2, but for large zooplankton (ZL).
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, NO3 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 biogeochemical processes in the ocean.

**Conclusions**

The data assimilation system is a powerful tool to investigate the ocean biogeochemical 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 biogeochemical processes in the North Pacific, especially in the Kuroshio extension region. We are now developing a coupled physical and biogeochemical model with resolving meso-scale variabilities. 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 biogeochemical 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 biogeochemical 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 biogeochemical processes. The data assimilation system for state estimation can provide the initial conditions of the numerical prediction, and the predictability of the biogeochemical 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 biogeochemical circulation. The combination of such advanced parameter estimation and stated estimation is necessary to obtain a more realistic circulation of the physical and biogeochemical field.

**References**


