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Study on environmental impacts onto oceanic material cycling by purposeful sequestration of CO_2 in the ocean（Abstract of the Final Report）

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1. Introduction

As a measure for control of the atmospheric carbon dioxide (CO_2) concentration, purposeful CO_2 sequestration into the ocean is considered as one of the most useful and effective options. As COP-7 in 2002 requested IPCC to evaluate technologies for CO_2 recovery, purification, isolation and sequestration, international science communities have examined the oceanic CO_2 sequestration technology as a realistic option. We, Japanese scientists, also should join to the international activities and contribute to establishment of Japanese strategy for the global warming problem.

The oceanic CO_2 sequestration technology is now considered as a technology by which liquid CO_2 which is collected directly and efficiently from exhaust gas of power plants and large factories are released into bathypelagic layer, 1,000-3,000 m depth. The released CO_2 will dissolve in the ambient seawater and the abundant CO_2 is expected to be isolated and preserved in the deep ocean for long time with no contact to the atmosphere. Although the density of biomass is low in comparison with those in epipelagic layer and sea floor, there is large variation of life from microorganisms to large animals in the bathypelagic layer. Furthermore, the layer is recognized as the important site for regeneration of nutrients as well as decomposition of organic matter. In promotion of the oceanic CO_2 sequestration, careful and sufficient investigation must be conducted for environmental assessments of the technology in conjunction with:

1. evaluation of the direct impact of the high CO_2 and low pH water on individual organisms and ecosystems, and
2. evaluation of the impact of the high CO_2 and low pH condition on marine material cycling by alteration the various chemical and biological processes.

As potential concerns of CO_2 sequestration, acute and chronic influences of high CO_2 condition have been investigated on some species of fish and zooplankton[1]. To our knowledge, the investigations of the impacts on oceanic material cycling have previously been made in any oceanic environments. Given the recent observations on the global warming and ocean acidification[2,3], there is heightened motivation to understand the advantage and impacts of ocean CO_2 sequestration. The analyses and models in this project will provide a comprehensive data set on potential impacts of CO_2 sequestration on marine ecosystems.

2. Research objectives

The project addresses a specific set of hypotheses concerning the potential impacts on oceanic material cycling and ecosystems by oceanic CO_2 sequestration. The working hypotheses underlying are:

1) Ocean CO_2 sequestration produces high CO_2 concentration and low pH water masses in the bathypelagic layer adjacent to disposal sites.
2) Dissolution of sinking $CaCO_3$ particles are enhanced by changes in carbonate chemistry induced by CO_2 sequestration.
3) The rates and extents of bacteria-related organic matter degradation and nutrient regeneration change with increasing CO_2 concentration and decreasing pH.

Accordingly, the goals of this project are (1) to determine the kinetics and the associated parameters of $CaCO_3$ dissolution in the enhanced CO_2 concentration; (2) to simulate the impact of CO_2 sequestration on sinking $CaCO_3$ dissolution particle flux; (3) to investigate the activities of bacteria which promote organic matter degradation and nutrient regeneration under low pH condition. These will be done through extensive field observations, laboratory experiments and model simulation. This project is expected to provide broader impacts on further developments in CO_2 ocean sequestration technology and mitigation options for environmental effects.

3. Research Methods, Results and Discussion

(1) Enhancement of $CaCO_3$ dissolution by oceanic CO_2 sequestration

As well as organic matter, $CaCO_3$ is produced biologically in the epipelagic layer and acts as a transporter of carbon to the deeper layer and the bottom sediments[4)]. It is assumed that change in carbonate chemistry in seawater induced by CO_2 sequestration enhances $CaCO_3$ dissolution. During this research project, we have measured the dissolution rate of a $CaCO_3$ analogue, planktonic foraminifera *Globigerinoides sacculifer*, under the experimental conditions simulated bathypelagic environment with various CO_2 concentrations and pH. Dissolution of $CaCO_3$ in seawater is a function of the degree of undersaturation and can be described by the equation[5-10)]:

$$R = k(1-\Omega)^n \qquad (1)$$

where R is the dissolution rate (%/day), k is a rate constant, Ω is the saturation state. The regression analysis using the experimental data during the present study then provided the equation:

$$R = 24.1 \times (1-\Omega)^{2.64} \qquad (2)$$

with the correlation coefficient of 0.93.

To date, because of practical difficulties in deep ocean operation and legal regulations by the international conventions, there are few opportunities to execute *in situ*, macro-scale experiments for CO_2 sequestration in the ocean environments. Instead, simulation model experiment is a useful tool to predict the behavior of the injected liquid CO_2, the diffusion of high CO_2 water masses and incidental environmental effects induced by CO_2 sequestration. We have employed a numerical model simulating the distribution of injected CO_2, which was developed using the Earth Simulator by our collaborator. The model is based on a practical scenario of oceanic CO_2 sequestration where 50 Mton CO_2 per year is continuously injected to 1,000-2,500m depth within the area at 19-22°N, 133-134°E (100 x 333km) in the western North Pacific for 30 years by moving ships[11, 12]. As well, there are available datasets to calculate $CaCO_3$ dissolution rate and the related parameters, including the sinking particle flux database that had been developed in the early stage of this study and the North Pacific Ocean physico/chemical database especially focusing on carbonate system that has being constructed in AIST. Coupling the model with these datasets, precise 3-D maps could be illustrated for the time-series distributions of the saturation depth of $CaCO_3$, *in situ* Ω values as well as $CaCO_3$ dissolution rate at optional location, depth and time. For example, Figures 1 shows horizontal distributions extracted from the 3-D simulation map. It was shown that the saturation depth of $CaCO_3$ shallows to 10-500 m in the relatively large area. Decrease in $CaCO_3$ flux was detected however in the restricted area adjacent to the injection site. Furthermore, the difference in the fluxes before and after 30-years injection was quite small, 0.01 $mg/m^2/day$ corresponding to less than 0.05% of the initial flux. The result suggests that the effect of CO_2 sequestration is moderate on $CaCO_3$ flux in the scenario used here.

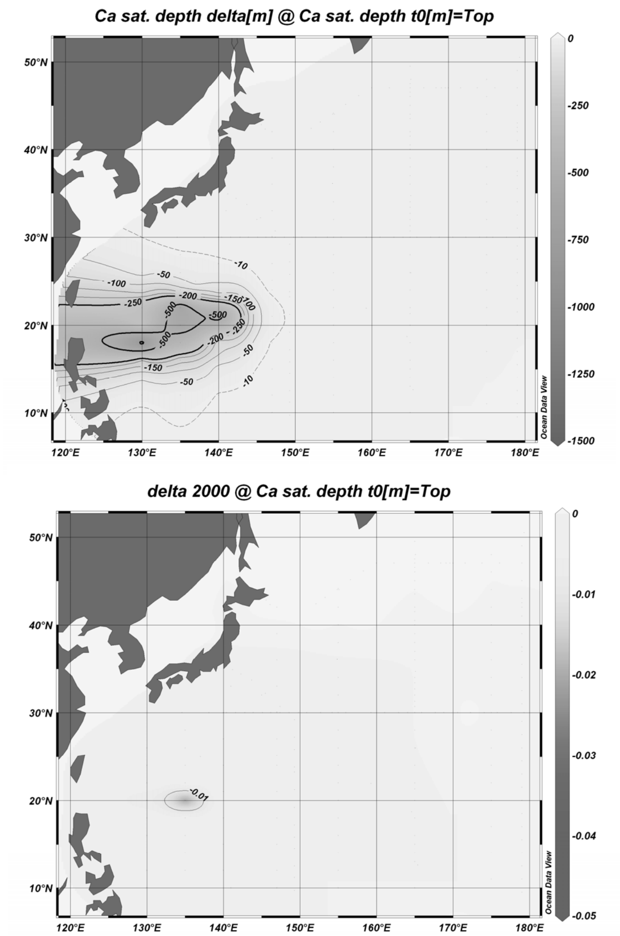

Figure 1. The predicted distributions of the $CaCO_3$ saturation depth (m) (upper) and the 2,000 m depth surface $CaCO_3$ flux ($mg/m^2/day$)(lower) after 30-years continuous CO_2 injection, which are expressed as the difference from the initial conditions.

(2) Impact on bacterial metabolisms and activities.

It is known that bacteria are the dominant organisms in the bathypelagic zone[13], contributing significantly to carbon and nutrient cycling through consumption, assimilation and decomposition of organic matter[14]. In this study, the effects of increase in CO_2 concentration and pH decrease on bacterial activities were examined under laboratory conditions. Seawater was collected from 2,000 m depth of off *Kuroshio*. In order to distinguish the impacts of increase CO_2 concentration and pH decrease, respectively, two methods were employed to acidify the seawater: 1) by bubbling with air containing various concentrations of CO_2 (up to 10,000 ppm) and 2) by addition of a chemical buffer solution of Tris-maleic acid mixture. The samples were incubated for 14 days and bacterial abundance and production rate (^{3}H-leucine incorporation rate) were measured (Fig. 2).

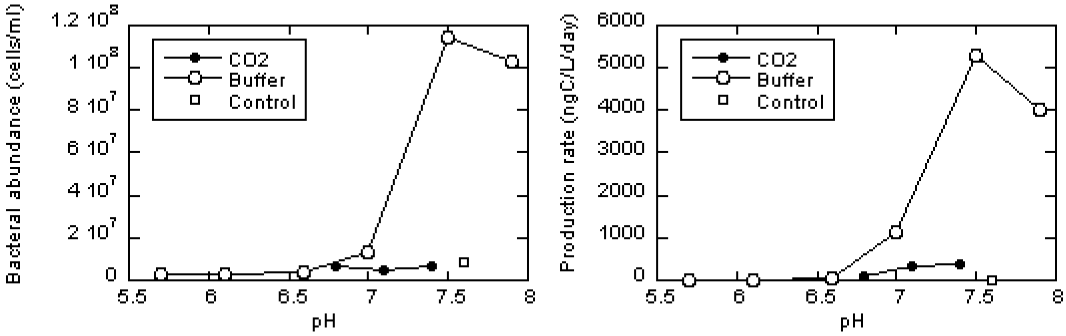

Figure 2. Bacterial abundance (left) and production rate (right) in the seawater acidified by the CO_2 and buffer treatments.

No significant impact was observed in the CO_2 treated samples, while in the buffer treatment both bacterial abundance and production rate were considerably increased within weak alkaline conditions and significantly decreased with acidification. From the result of the CO_2 treatment, the effect of the increase in CO_2 concentration seems to be relatively moderate for bacterial activities. This is most likely due to difficulty in detection of small changes in activities of bathypelagic bacteria originally exhibiting quite low biomass and metabolism. On the contrary, it can be considered that the bacterial activities were enhanced by enrichment of organic substrates, which was derived from the buffer reagent. Within the weak basic region similar to the ambient condition, the activities increased with the additional available substrates, and the growth and production were suppressed with acidification. Although the bathypelagic layer is mostly occupied by low biomass water mass, biologically active sites also exist including the surface of suspended and sinking particles enriched with organic matter. They are often called as microbial “hot spot” where attached bacteria play important roles in bathypelagic material cycling through dissolution and decomposition of organic matter[15]. Resultingly, our buffer experiment examined the impacts of acidification on bacterial assemblage in the “hot spot”. Even though CO_2 sequestration causes minor influence on dominant free living bacteria, the potential effects on the attached microbes should be further investigated.

During the experiments using abundance and production rate as the indexes of bacterial metabolism, it was suggested that some specific groups of bacteria exhibited high activities in the buffer treatment, but not bulk bacterial community. For quantitative evaluation of the presence of and the acidification impacts on such specific bacteria, the abundance of viable cell was examine, which was experimentally defined as coupulent or elongated cell in the presence of a cell-division inhibitor, nalidixic acid. Figure 3 shows some epi-fluorescent micrographs.

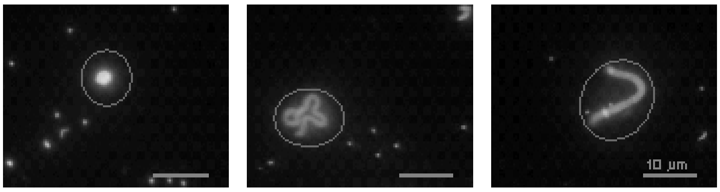

Figure 3. Epifluorescent micrographs of bacteria incubated in the buffer experiment. The coupulent or elongated cells are the viable cells and the small white dots in the background are other, inactive bacteria.

The result was quite consistent with those obtained in total bacterial abundance and production rate. The abundance of the viable cell was high, 10% of the total cells, in weak basic condition and considerably decreased (~3%) with acidification. Although the viable bacteria are the minority of bacterial community, they seem to be the principal players in the bacteria-related biological processes in bathypelagic zone. Very recently, archaea and some unidentified microorganisms have been found, having specific functions and metabolisms in the mesopelagic and bathypelagic layer[16]. Identifying the species and understanding the functions of the viable bacteria found in this study are important issues to evaluate the potential effects of CO_2 sequestration and also contribute the progress in marine microbiology in the twilight zone of the bathypelagic layer.

4. Conclusive remarks

Under the restricted circumstance of operation of *in situ* macroscale experiments for oceanic CO_2 sequestration, laboratory experiments and numerical simulations as used in this study are useful options for quantitative evaluation of the potential impact of the technology. The results suggested relatively moderate effects on the dissolution kinetics of $CaCO_3$ sinking particle in the given scenario. However, there is the possibility that small change in fluxes within the bathypelagic layers results in significant, chronic impacts of sea-bed, benthic ecosystems by altering the energy supply from the epipelagic layer. Furthermore, the used scenario selected a sub-tropical area as the CO_2 injection site where detection of change in $CaCO_3$ dissolution rate seems to be difficult. Since sub-tropical bathypelagic layer is highly saturated for $CaCO_3$, in part over-saturated, small change in carbonate systems can cause no significant change in the dissolution rate. On the other hand, high latitude areas exhibit higher flux of $CaCO_3$ and generally low saturation state, and hence the environments might be sensitive for CO_2 sequestration. The appropriate environmental assessment needs precise planning of synthesis research for construction of practical scenario of CCS, numerical simulation, collection of *in situ* physical, chemical and biological data around the operation site .

The novel technique using the viable cell as an index for bacterial metabolisms proposed in this study can be expected as a useful tool in the environmental assessment and monitoring of CO_2 sequestration. Without the use of radio-isotope labeled reagents, the viable cell method is more simple and suitable in both onboard and laboratory experiments. As well as bacterial metabolisms, this study has supposed some potential impact of acidification induced by CO_2 sequestration including extracellular hydrolytic enzymes for organic matter decomposition and nutrient regeneration. Some quantitative data could be presented by laboratory experiments, but the practical application of the results for precise estimation of the environmental impacts is still limited. In order to provide quantitative and visualized results of environmental impacts in such biological and biochemical processes, actually the available data from *in situ* marine environments is scant.

Very recently, ocean surface acidification has been recognized as a global scale environmental problem in connection with increase in the atmospheric CO_2 concentration[2)]. It is undoubtable that the surface acidification is one of most serious concerns for marine ecosystems. In some international framework, e.g., OSPAR Convention, the threat of ocean surface acidification is forcibly linked to the potential risks from oceanic CO_2 sequestration, though these two phenomenons should be discussed separately as a related, but independent problems. At the same time, through publications of the IPCC reports, and the discussion in G8 Summit, the significance and exigency of global climate change has been universally accepted as a public concern, and effective mitigation options are strongly required. To keep oceanic CO_2 sequestration as a potentially important option to reduce CO_2 emission to the atmosphere, we must continuously provide scientifically available data and knowledge on their risk and benefit.

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