

# EVALUATION OF THE EFFECT OF THE CO<sub>2</sub> OCEAN SEQUESTRATION ON MARINE LIFE IN THE SEA NEAR THE JAPAN USING A NUMERICAL MODEL

Tomoaki NAKAMURA<sup>1\*</sup>, Akira WADA<sup>1</sup>, Kazuyuki HASEGAWA<sup>2</sup>  
and Minoru OCHIAI<sup>3</sup>

<sup>1</sup>Nihon University, Advanced Research Institute for the Science and Humanities  
(6F, Ichigaya Tokyu-Bldg., Kudan-Kita 4-2-1, Chiyoda-ku, Tokyo, 102-0073, Japan)

<sup>2</sup>Marine Ecology Research Institute  
(300, Iwawada, Onjuku, Isumi, Chiba, 299-5105, Japan)

<sup>3</sup>Nihon University, College of Industrial Technology  
(1-2-1, Izumicho, Narashino, Chiba, 275-8575, Japan)

\* E-mail: [adto06003@g.nihon-u.ac.jp](mailto:adto06003@g.nihon-u.ac.jp)

CO<sub>2</sub> oceanic sequestration is one of the technologies for reducing the discharge of CO<sub>2</sub> into the atmosphere, which is considered to cause the global warming, and consists in isolating industry-made CO<sub>2</sub> gas within the depths of the ocean. This method is expected to enable industry-made CO<sub>2</sub> to be separated from the atmosphere for a considerably long period of time.

On the other hand, it is also feared that the CO<sub>2</sub> injected in the ocean may lower pH of seawater surrounding the sequestration site, thus may adversely affect marine organisms.

For evaluating the biological influences we have studied to precisely predict the CO<sub>2</sub> distribution around the CO<sub>2</sub> injection site by a numerical simulation method.

In previous studies, in which a 2 degree by 2 degree mesh was employed in the simulation, CO<sub>2</sub> concentrations tended to be evenly dispersed within the grid, giving lower concentration values. Thus, the calculation accuracy within the area several hundred kilometers from the CO<sub>2</sub> injection site was not satisfactory for the biological effect assessment.

In the present study we improved the accuracy of concentration distribution by changing a computational mesh resolution for a 0.2 by 0.2 degree mesh.

By the renewed method we could obtain detailed CO<sub>2</sub> distribution in waters within several hundred kilometers of the injection site, and clarified that the Moving-ship procedure may have less effects of lowered pH on marine organisms than the fixed-point release procedure of CO<sub>2</sub> sequestration.

**Key Words :** *The global warming, Carbon dioxide, The Pacific Ocean, CO<sub>2</sub> Ocean sequestration, pH , influence to marine life*

## 1. INTRODUCTION

The large scale consumption of fossil fuels, which is increasing year by year together with economic growth, is believed to be the principal cause of the global warming problem; and great concern is being directed at the accompanying increase of carbon dioxide emissions. In November 1988, the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) jointly established the Intergovernmental Panel on Climatic Change (IPCC). Together with this worldwide

development, in 2005 the United Nations Framework Convention on Climatic Change (UNFCCC), which sets up an international framework to prevent global warming, and the Kyoto Protocol, were established by major international agreements. The Kyoto Protocol requires nations to reduce greenhouse gases at a fixed rate (6% in the case of Japan) during the period 2008 to 2012. However, the global warming problem will have its main impact in the future, and the burden of taking countermeasures is large, so the present reality is that specific countermeasures are lagging. Bringing about a large decrease in carbon

dioxide emissions without changing our present social system is difficult.

Naturally, part of the effort will have to involve increasing the efficiency of energy usage, but there is also a need to promote research and development work on measures to suppress carbon dioxide generation and on Carbon dioxide Capture and Storage (CCS)<sup>1)</sup>. Although carbon dioxide in the atmosphere passes through the air – sea interface to dissolve in the ocean surface layer, under natural conditions the rate at which atmospheric carbon dioxide is transported to intermediate layer and deep ocean water is slow because of the stable density stratification. CCS is being developed for the purpose of directly injecting carbon dioxide into intermediate and deep layers of the ocean, where it will be dissolved and absorbed. This technology is capable of dealing with the large quantities of carbon dioxide which are presently being emitted, and it is expected that it will be capable of long – term storage. In the present research we investigate the possibility of oceanic storage of carbon dioxide by means of carbon dioxide behavior prediction simulation analysis. First of all, since carbon dioxide injected into the ocean is advected and diffused as it spreads, it is necessary to accurately determine the flow field in the ocean.

Most present research on oceanic storage of carbon dioxide focuses on the global scale. Nakashiki et al.<sup>2)</sup> did a calculation assuming that carbon dioxide is injected into the ocean near Japan (Area I 145 ° to 155 ° E 20 ° to 30 ° N, Area II 155 ° to 165 ° E 30 ° to 40 ° N) and determined the percentage of carbon dioxide that is in water shallower than 400m after 200 years. Tejima et al.<sup>3)</sup> investigated the effect of initial dilution of carbon dioxide injected from the injection pipe by means of a 3-dimensional investigation of flow and vortices in the back flow in the pipe holes, and determined the characteristics of a pipe that will be capable of stable transport and injection of carbon dioxide. Masuda et al.<sup>4)</sup> discussed the effect of difference of injection depth on carbon dioxide injected into the ocean near Japan, but they failed to consider important processes of the oceanic carbon circulation such as carbon dioxide interchange at the air – sea interface, and vertical transport of carbon by organisms (the biological pump). Sorai and Ohsumi<sup>5)</sup> partitioned the global ocean into 19 boxes, and investigated oceanic carbon circulation processes including the solubility pump, the biological pump and the alkaline pump. They also considered acidification of the ocean due to exchange of the increasing anthropogenic carbon dioxide in the atmosphere with oceanic carbon dioxide.

In the present research, in order to evaluate the

possibility of oceanic sequestration, we constructed a model that would permit the effect of marine organisms to be considered. In the initial stage of this research, we have computed the flow in the Pacific Ocean and simulated oceanic sequestration of carbon dioxide offshore of Kona, Hawaii<sup>6)</sup> and in the ocean near Japan<sup>7)</sup>. In calculating the 3-dimensional circulation in the Pacific Ocean, we used data on the wind over the ocean received from NASA and determined the 3-dimensional flow field in the Pacific Ocean (see Fig. 1). The result of that calculation, at least as far as surface flow is concerned, agreed approximately with results previously published in the literature and with observations (the average surface flow field obtained from buoy tracks) by the Japan Coast Guard. In addition, the effect of data assimilation has been incorporated into the equations of conservation of temperature and salinity, and it has been shown that this is an effective means of reproducing the ocean flow field<sup>8)</sup>.

In addition, we have done calculations to reproduce the concentrations of radioactive nuclei in order to check the accuracy of the flow field in intermediate and deep layers. Based on this result, we checked the appropriateness of the oceanic flow model, and decided to apply a carbon dioxide ocean diffusion model. Until now, with a horizontal resolution of 2degree by 2degree, the concentration of the injected carbon dioxide has been averaged within the mesh and therefore has been somewhat low. Throughout most of the Pacific Ocean, more than a few hundred kilometers from the injection point, this analysis is adequate, but within several tens of kilometers of the injection point, the pH is nearly unchanged, which is different from what happens in the real ocean, so this model was not very effective in evaluating the biological effect. In the present research, in order to make it possible to evaluate the biological effect within a few tens of kilometers of the injection point, the existing model was used but this time with a horizontal resolution of 0.2degree by 0.2degree, with the aim of improving the prediction of carbon dioxide concentration. In addition, the computational accuracy of the model was improved by introducing an atmosphere in which the carbon dioxide concentration is continually increasing, the carbon exchange between that atmosphere and the ocean surface, and the vertical circulation of carbon due to the effect of phytoplankton (the biological pump), into the model.

## 2. Pacific Ocean Circulation Model

### (1) Partition of the calculation region

The calculation region was the entire Pacific Ocean:  $110^{\circ}\text{E}$  to  $70^{\circ}\text{W}$ ,  $60^{\circ}\text{N}$  to  $74^{\circ}\text{S}$ , C grid. Changing from a 2degree by 2degree grid to a much finer 0.2degree by 0.2degree grid greatly increases the calculation load, so we used the finer grid only in the region near the point where the carbon dioxide was injected, at  $133^{\circ}\text{E}$   $23^{\circ}\text{N}$ . The fine grid was used in a region centered on the injection point, from  $127^{\circ}\text{E}$  to  $139^{\circ}\text{E}$  and from  $17^{\circ}\text{N}$  to  $25^{\circ}\text{N}$ . The mesh was also variable in the vertical direction: the number of layers in the vertical was increased from 11 to 16 throughout the ocean (see Table 1).

### (2) Analysis method

The fundamental equation system as well as the boundary condition, the wind stress on the sea surface was the same as the report by Nakamura et al.<sup>7)</sup>. In this research, an 0.2degree by 0.2degree fine mesh system was nested inside the original 2degree by 2degree coarse mesh system.

The velocity obtained from the coarse grid at the boundary of the fine grid is interpolated as the means of transmitting momentum to the fine mesh. Information is transmitted back from the fine mesh to the coarse mesh by simultaneously solving the pressure Poisson equations for the degrees of freedom of the fine mesh and the coarse mesh, so that transport is strictly conserved. The pressure Poisson equations were solved by using the conjugate residual finite difference method with incomplete Cholesky decomposition on the structured mesh. If nesting is performed, and a solver using matrices is used, in connecting the blocks the coefficient matrix becomes irregular; even if a structured mesh is used, the unstructured mesh solver must be used, increasing the work of programming and the computational cost. For these reasons, we decided to use a method involving a structured mesh solver that does not use a matrix expression<sup>9)</sup>. In doing this, we used an unweighted finite difference method based on the Stokes theorem<sup>10)</sup>.

The flow field before introduction of the fine mesh is shown in Fig. 2, the flow field after introduction of the fine mesh in Fig. 3. Comparing Figs. 2 and 3, overall the flow is clockwise, with large velocities at  $134^{\circ}\text{E}$  to  $140^{\circ}\text{E}$   $17^{\circ}\text{N}$ , and at  $127^{\circ}\text{E}$   $20^{\circ}\text{N}$  to  $26^{\circ}\text{N}$ . At  $134^{\circ}\text{E}$  to  $140^{\circ}\text{E}$   $25^{\circ}\text{N}$  a clear difference is seen between Figs. 2 and 3. This is believed to be due to the effect of interpolation from the coarse mesh. In addition, in the results of the calculation a deep layer flow along bottom contours is seen to result from introduction of the fine mesh.

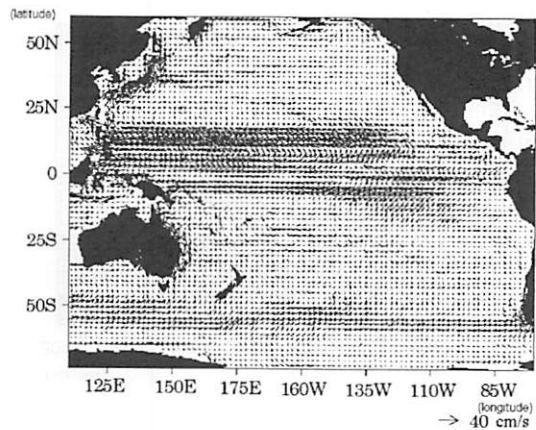


Fig. 1 Calculated flow field over the whole Pacific Ocean at 10m depth

Table 1 Bottom depths and Thickness of Model Levels

| Layer    | After subdivision |              | Before subdivision |              |
|----------|-------------------|--------------|--------------------|--------------|
|          | Depth(m)          | thickness(m) | Depth(m)           | thickness(m) |
| 1 layer  | 20                | 20           | 20                 | 20           |
| 2 layer  | 50                | 30           | 50                 | 30           |
| 3 layer  | 100               | 50           | 100                | 50           |
| 4 layer  | 200               | 100          | 200                | 100          |
| 5 layer  | 400               | 200          | 400                | 200          |
| 6 layer  | 600               | 200          | 800                | 400          |
| 7 layer  | 800               | 200          |                    |              |
| 8 layer  | 1000              | 200          | 1500               | 700          |
| 9 layer  | 1250              | 250          |                    |              |
| 10 layer | 1500              | 250          |                    |              |
| 11 layer | 1750              | 250          | 2500               | 1000         |
| 12 layer | 2000              | 250          |                    |              |
| 13 layer | 2500              | 500          |                    |              |
| 14 layer | 3500              | 1000         | 3500               | 1000         |
| 15 layer | 4500              | 1000         | 4500               | 1000         |
| 16 layer | 5500              | 1000         | 5500               | 1000         |

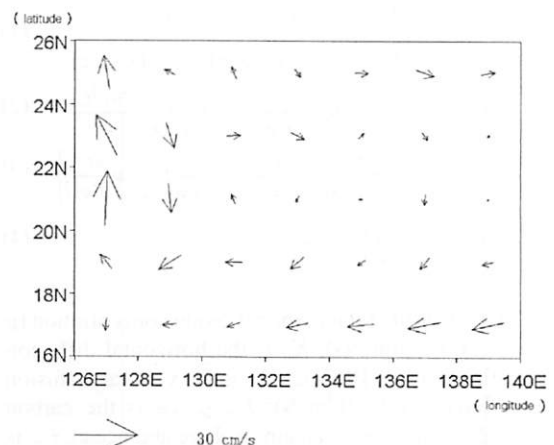


Fig. 2 Calculated flow field with 2 degree square grid at 10m depth

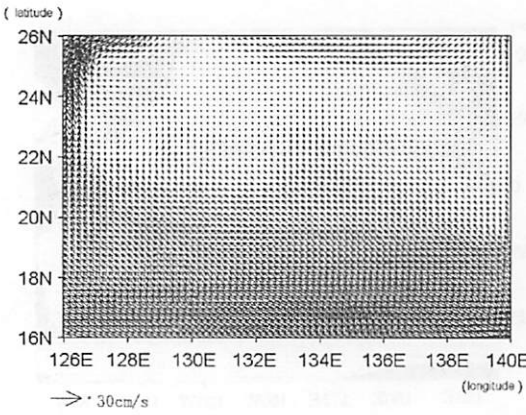


Fig. 3 Calculated flow field with 0.2 degree square grid at 10m depth

### 3. CALCULATION MODEL TO PREDICT CARBON DIOXIDE BEHAVIOR

#### (1) Outline of carbon dioxide concentration calculation

Next, we present an outline of carbon dioxide concentration diffusion. Using the same grid system that is used for the flow model, we constructed a model with a fine grid near the carbon dioxide injection point. In this model, the carbon dioxide exchange is given as the boundary condition at the air-sea interface, in constructing a model that considers the vertical transport of carbon due to biological activity (the biological pump) due to the amount of primary production determined by Breger<sup>11)</sup>. The calculation formula used in the analysis is given as Equation (1) to (4).

$$\frac{\partial C}{\partial t} + L(C) = K_H D_H(C) + K_V D_V(C) \quad (1)$$

$$-F_{OCEAN-AIR}(\lambda, \varphi) + F_{inj}(\lambda, \varphi, z) - F_{bio}(\lambda, \varphi, z) \quad (2)$$

$$L(C) = \frac{1}{r \cos \varphi} \left\{ \frac{\partial}{\partial \lambda} uC + \frac{\partial}{\partial \varphi} v \cos \varphi C \right\} + \frac{1}{r^2} \frac{\partial w r^2 C}{\partial r}$$

$$D_H(C) = \frac{1}{r \cos \varphi} \left\{ \frac{1}{r \cos \varphi} \frac{\partial^2 C}{\partial \lambda^2} + \frac{1}{r} \frac{\partial}{\partial \varphi} \left( \cos \varphi \frac{\partial C}{\partial \varphi} \right) \right\} \quad (3)$$

$$D_V(C) = \frac{1}{r^2} \frac{\partial}{\partial r} \left\{ r^2 \frac{\partial C}{\partial r} \right\} \quad (4)$$

Here,  $C$  is the total carbon dioxide concentration ( $\mu$  mol/kg),  $t$  is time (s),  $K_H$  is the horizontal diffusion coefficient ( $1.0 \times 10^3 \text{ m}^2/\text{s}$ ),  $K_V$  is the vertical diffusion coefficient ( $1.0 \times 10^{-4} \text{ m}^2/\text{s}$ ),  $F_{OCEAN-AIR}$  is the carbon dioxide budget between atmosphere and ocean,  $F_{inj}$  is the amount of carbon dioxide injected ( $\mu$  mol/kg  $\cdot$  s),  $F_{bio}$  is the amount of transport by the biological pump ( $\mu$  mol/kg  $\cdot$  s),  $\lambda$  is the spherical latitude coordinate and  $\varphi$  is the spherical longitude coordinate,  $u$ ,  $v$ ,  $w$  is

eastward, northward and upward velocity components (m/s),  $r$  is radius of the earth (m).

#### (2) Carbon dioxide exchange between atmosphere and ocean

The amount of carbon dioxide exchanged through the ocean surface (the carbon dioxide budget between atmosphere and ocean) varies depending on the difference of carbon dioxide partial pressure between the atmosphere and ocean surface. That is to say, the higher the partial pressure in the atmosphere, the more carbon dioxide that is absorbed from the atmosphere into the ocean; the higher the partial pressure in the ocean, the more carbon dioxide that is released from the ocean into the atmosphere. The carbon dioxide budget between atmosphere and ocean is calculated using the following equation.

$$F_{OCEAN-AIR} = E \cdot (pCO_{2-OCEAN} - pCO_{2-AIR}) \quad (5)$$

Here,  $E$  is the gas exchange coefficient ( $\text{mol}/\text{m}^2 \cdot \text{s} \cdot \text{atm}$ ),  $pCO_{2-OCEAN}$  is the partial pressure of carbon dioxide in the ocean ( $\mu$  atm) and  $pCO_{2-AIR}$  is the partial pressure of carbon dioxide in the atmosphere ( $\mu$  atm).

Near land, where there is a direct effect of fossil fuel combustion, the partial pressure of carbon dioxide varies from one place to another; but the present research is concerned with the whole Pacific Ocean, throughout most of which the partial pressure of carbon dioxide varies little with location. Therefore, we assumed it to have a fixed value. Since the concentration of carbon dioxide in the atmosphere is continually increasing, we assumed an annual rate of increase of 1.8ppm. Meanwhile, since the partial pressure of carbon dioxide in the ocean varies greatly from one ocean region to another, and observed values are few, we computed it from the equation of Suzuki<sup>12)</sup>. The partial pressure in the ocean is believed to depend on several parameters including water temperature, salinity, total carbon dioxide concentration and total alkalinity.

$$pCO_{2-OCEAN} = \frac{[CO_2(aq)]}{K'_H} \quad (6)$$

Here  $[CO_2(aq)]$  is the concentration of non-dissociated carbon dioxide, and  $K'_H$  is the solubility of carbon dioxide ( $\text{mol}/\text{kg} \cdot \text{atm}$ ).

The sign of the budget is determined by the partial pressure difference, but the rate of exchange is believed to be greatly affected by the wind near the ocean surface.  $E$  in Equation (5) (the gas exchange coefficient) depends on the wind: it is a parameter that determines the rate of exchange. Many values of

this parameter have been reported; it is not presently clear which is the most realistic. In the present research, long term wind speed data provided by NASA are being used to determine the effect of wind. We have used the following equation for  $E$  which was first reported by Tans et al.<sup>13)</sup>

$$\begin{aligned} E &= 0.016(U-3) & : U > 3 \text{ m/s} \\ E &= 0 & : U \leq 3 \text{ m/s} \end{aligned} \quad (7)$$

Here  $U$  is the wind speed (m/s). According to this equation, if the wind speed is not more than 3m/s, carbon dioxide will not be exchanged between the ocean and atmosphere.

Next we look at whether the method we are using to determine carbon dioxide exchange between the atmosphere and ocean is appropriate. The difference of carbon dioxide between ocean and atmosphere calculated using Equations (5) to (7), together with the difference of carbon dioxide partial pressure between atmosphere and ocean calculated by Nojiri<sup>14)</sup> for the subpolar region, is shown in Fig. 4. According to these results for the subpolar region of the North Pacific Ocean, the negative of values are preponderant. A negative value means that carbon dioxide is being absorbed from the atmosphere into the ocean. Calculations from the observed values obtained by Takahashi et al.<sup>15)</sup> and Nojiri<sup>14)</sup> also make it clear that this is a region of absorption of carbon dioxide by the ocean. In addition, from Fig. 4, comparing with the observational results of Nojiri<sup>14)</sup>, the results of our model reproduce the observations reasonably well, although there are some differences in partial pressure values in the vicinity of the North American continent, in the center of the subpolar region.

### (3) The biological pump

In the oceanic carbon circulation, in addition to ocean – atmosphere carbon dioxide exchange at the ocean surface, there is an important circulation due to marine organisms. At the ocean surface, phytoplankton create organic carbon from inorganic carbon by photosynthesis using carbon dioxide dissolved from the atmosphere, and nutrients, as raw materials. This is called “primary production”. Organic carbon produced in this way is used by “consumers” (macroplankton and fishes). Organic carbon that is not used falls out of the euphotic zone (down to 200m) into the intermediate and deep layers where it decomposes and the decomposition products are consumed to return the carbon to the form of inorganic carbon.

An outline of this transport of carbon from the euphotic zone to the lower layers, called the biological pump, is shown in Fig. 5<sup>16),17),18)</sup>. Because

of differences in the supply of nutrients, primary production is divided into regenerated and new production. Regenerated production is the production of organic matter using nutrients that have been decomposed and regenerated inside the euphotic zone, and is unrelated to the transport of organic carbon from the surface layer to the deep layer. Meanwhile, new production is the production of organic matter using nutrients transported into the ocean surface layer by upwelling from intermediate and deep layers, and transported from rivers and the atmosphere. In a steady state it equals the amount of organic carbon transported from the surface layer to the intermediate and deep layers.

The amount of regenerated production is far greater than the amount of new production, but regenerated production does not contribute toward the transport of carbon, so in the present research only new production is treated. New production, which depends on the inflow of nutrients from outside of the system, is related to the amount of primary production. It is not clear what proportion of primary production consists of new production, but in general it is estimated to be about 10 %<sup>18)</sup>.

Construction of a model of the biological pump is difficult because of the many complicated elements and the lack of observations of amount of carbon

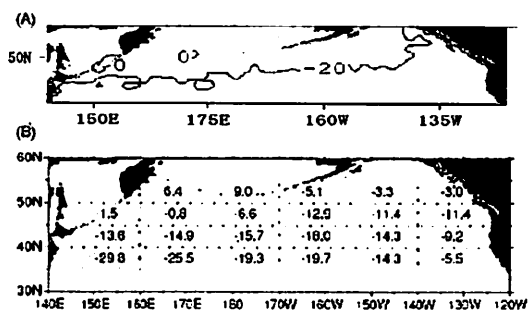


Fig.4 Comparison of  $\Delta p\text{CO}_2$  between the present calculated (A) and observed results (B) by Nojiri<sup>14)</sup>

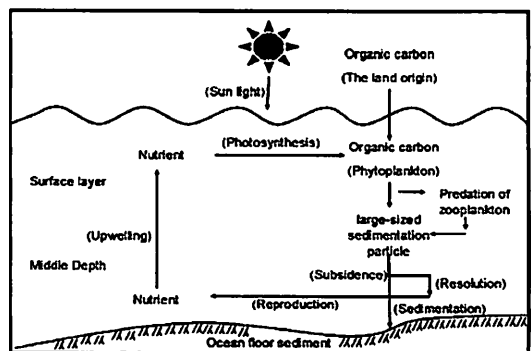


Fig.5 The concept of the biological pump<sup>18)</sup>

dioxide transport. In the present research we have used Equations (8) and (9) below, obtained by Eppley and Peterson<sup>19)</sup> to obtain the ratio of new production to primary production.

$$f = PP/410 \quad (<150) \quad (8)$$

$$f = PP/400 - PP/340000 \quad (150 \sim 500) \quad (9)$$

Here  $f$  is the ratio of new production to primary production, and  $PP$  is the amount of primary production ( $\text{gC} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ ). If the primary production is  $150(\text{gC} \cdot \text{m}^{-2} \cdot \text{year}^{-1})$  or less, then Equation (8) is used; if it is 150 to 500 ( $\text{gC} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ ), then Equation (9) is used.

In the present model, the amount of new production is taken to be the amount of carbon transported vertically by the biological pump. In the euphotic zone (layers 1 to 4 in the model), the amount corresponding to the transport is subtracted from the amount of carbon in the ocean; while in the intermediate layers (layers 5 to 13 in the model) the amount of sinking (downward transport) is added to the amount of carbon in the ocean. In addition, in Equations (8) and (9), the annual average by Berger<sup>11)</sup> was taken as the amount of primary production ( $PP$ ).

#### 4. PREDICTION OF $\text{CO}_2$ CONCENTRATION

##### (1) Injection method

The ocean absorbs  $\text{CO}_2$  from the atmosphere, but at a much slower rate than the release of  $\text{CO}_2$  by human activity. Not all  $\text{CO}_2$  that is emitted can be absorbed. Therefore,  $\text{CO}_2$  is stored in the ocean by injecting it directly, so that it does not have to pass through the oceanic surface layer where absorption is slow.

Storage of  $\text{CO}_2$  in the ocean is accomplished by separating and recovering the  $\text{CO}_2$  gas from combustion of fossil fuel, then transporting it to the oceanic interior to separate it from the atmosphere for a long time. Three methods of minimizing the impact of oceanic storage on the ocean environment have been conceived. One is to lay a pipeline from the plant on land where combustion takes place to a fixed point of known depth on the ocean bottom where the  $\text{CO}_2$  is injected. The second is to liquefy the recovered  $\text{CO}_2$  and then transport it in a boat to the target region where it is released through a pipe lowered from the boat while the boat moves at slow speed. This is called the moving ship method. The third is to release it at the ocean bottom in a region where there is believed to be practically no current or turbulence<sup>20)</sup> (deep water bottom mooring).

In the present research, the analysis was performed for the fixed point release method and the moving point release method. In the fixed point release method, it was assumed that  $\text{CO}_2$  was injected at a single fixed point. As regards the moving ship method, according to Ozaki<sup>21)</sup>, if a ship moves at 9km per hour, it can inject 0.1 ton of  $\text{CO}_2$  per second. In the present research, the computational time step was 3,600 seconds, and the horizontal grid was 0.2degree by 0.2degree (about 20km by 20km); it was assumed that the boat moved 1 grid spacing in 2 time steps, moving as shown in Fig. 6. After 100 time steps the boat returned to the geographical starting point and started over from point 1.

##### (2) Setting of the amount of $\text{CO}_2$ injected and the region in which it is injected

Public interest in global warming and energy saving are steadily increasing. According to Japan's Economic White Paper for fiscal 2006<sup>22)</sup>, although the amount of  $\text{CO}_2$  emitted in Japan in 2004 was less than that in the previous year, the amount of  $\text{CO}_2$  (actually  $\text{CO}_2$  equivalent) emitted in Japan in 2003 was 0.357Gtons-C. This value exceeded the amount of  $\text{CO}_2$  fixed by COP3 in 1990 (0.307Gtons-C) by about 0.052Gtons-C/year. Taking this excess amount of  $\text{CO}_2$  as the load, the increases of concentration were predicted for both fixed point release and moving point release.

The  $\text{CO}_2$  was assumed to be injected in Japan's Exclusive Economic Zone (EEZ) (see Fig. 7). This is because it can be expected that the amount of  $\text{CO}_2$  that can be stored in international waters will be limited by both international law and international treaties.

According to Takahashi et al.<sup>15)</sup>, the injection region is a region of net absorption of  $\text{CO}_2$ , so it is

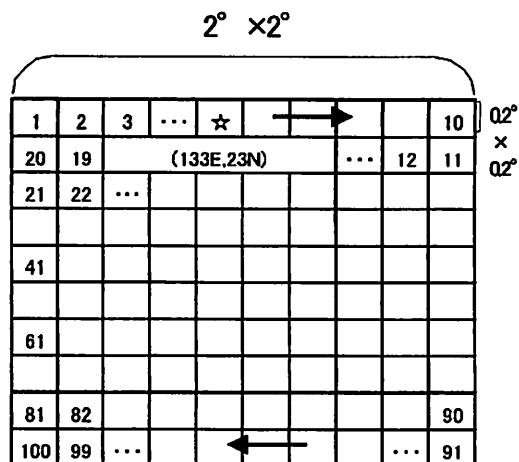


Fig.6 Navigation course of the moving ship

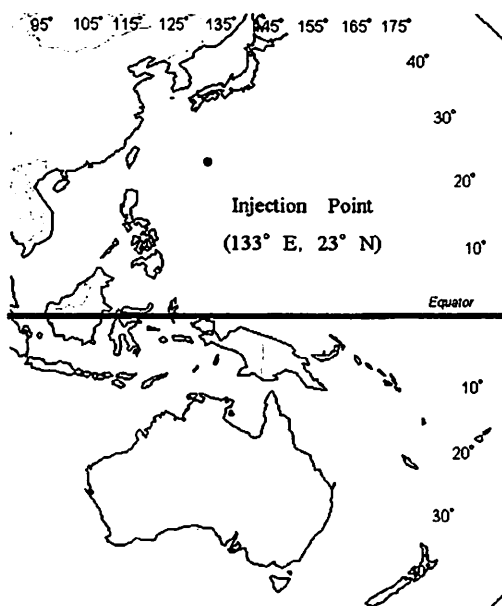


Fig.7 The CO<sub>2</sub> injection point in the sea near Japan island

expected that the injected CO<sub>2</sub> will not easily rise to the surface. The Japanese Research Institute of Innovative Technology for the Earth (RITE) is planning to inject CO<sub>2</sub> in the vicinity of 133 ° E 23 ° N in that region in Phase 2 of a CO<sub>2</sub> ocean storage project.

### (3) Result of CO<sub>2</sub> concentration prediction

First, in order to determine the depth at which CO<sub>2</sub> should be injected, CO<sub>2</sub> was injected into each of the layers at the target point and the results were compared at 10 years after the start of the calculation. Since storage of CO<sub>2</sub> in the ocean will not be effective if it is released into the atmosphere after a short time, and since many different types of organisms live in both the surface and deep layers of the ocean, the total amount of CO<sub>2</sub> arriving in the ocean surface layer and the total amount arriving in the bottom layer below 4,000m depth were compared. The surface layers (layers 1 to 4) and the bottom layers (layers 14 to 16) were excluded from the injection depths. These investigations were initially performed by Nakamura et al.<sup>7)</sup>. A finer mesh was also introduced in the vertical direction. The CO<sub>2</sub> concentrations are injected continuously into each layer for 10 years, and the initial vertical distribution of concentration (at the injection point) are shown in Fig. 8. The initial distribution for CO<sub>2</sub> were obtained from the data of water temperature and salinity (Chen-Tung et al., 1979)<sup>23)</sup>. From Fig. 8, it is seen that there was an increase of concentration in each injection layer, but in other layers

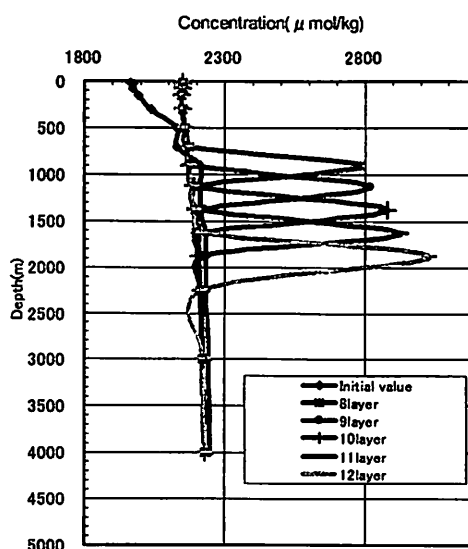


Fig.8 Initial and calculated distributions of CO<sub>2</sub> concentration in the vertical section (133°E 23°N)

the increase was small. In addition, the deeper the layer in which CO<sub>2</sub> is injected, the greater the concentration increase at the injection point, even though the volume of each box is nearly the same. This is believed to be because the deeper the injection layer, the smaller the current and the smaller the transport in the horizontal direction, so that the CO<sub>2</sub> tends to remain in the box into which it is injected. Meanwhile, from Fig. 8 it is also seen that the concentration increases somewhat from the initial value in the vicinity of the surface, but this is believed to be because the partial pressure of CO<sub>2</sub> in the atmosphere is increasing by 1.8 ppm/year, which increases the amount of atmospheric CO<sub>2</sub> dissolved into the ocean.

From the calculated result, it is seen that if CO<sub>2</sub> is injected into the 10th layer or deeper, the amount of CO<sub>2</sub> arriving in the euphotic zone (down to about 200m) is not more than about 0.5% of the total. Further, it was confirmed that in the case of injection into the 9th layer or shallower, the amount of CO<sub>2</sub> arriving at depths of 4,000m and greater is 3% or less. From economic considerations, and also according to Ohsumi<sup>24)</sup>, due to the density difference with sea water at depths of 3,000m and greater it is conceivable that CO<sub>2</sub> will sink, so that the 9th through 11th layers appear to be a suitable depth for CO<sub>2</sub> injection. In the present calculation, among the 9th to 11th layers, in order to minimize the amount of CO<sub>2</sub> that escapes to either shallower or deeper water the 10th layer appears to be the optimum depth at which to inject CO<sub>2</sub>.

Next, based on this result, we attempted to determine the difference in concentration increase



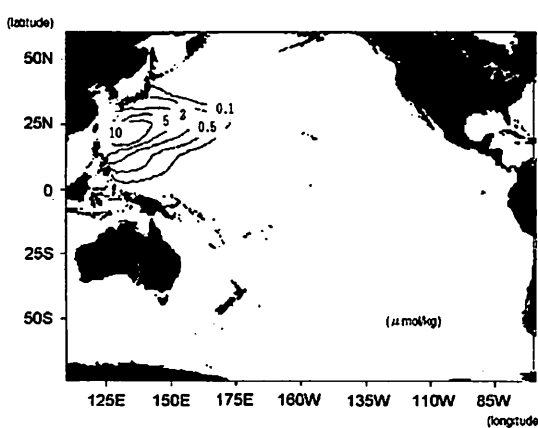


Fig.9 CO<sub>2</sub> concentrations with 2 degree square grid (Layer 7, 1,150m depth) after 10 years

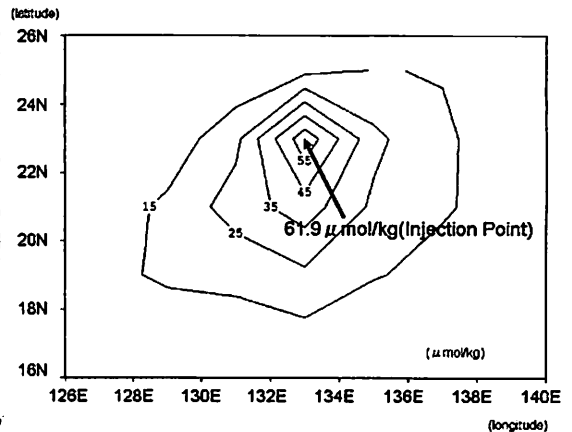


Fig.11 CO<sub>2</sub> concentrations with 2 degree square grid (Layer 7, 1,150m depth) after 10 years (enlarged view)

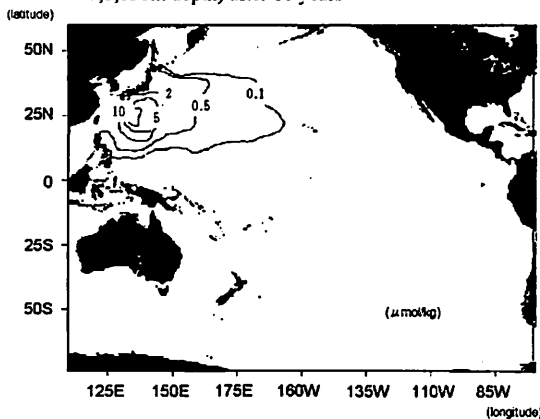


Fig.10 CO<sub>2</sub> concentrations with 0.2 degree square grid (Layer 10, 1,375m depth) after 10 years

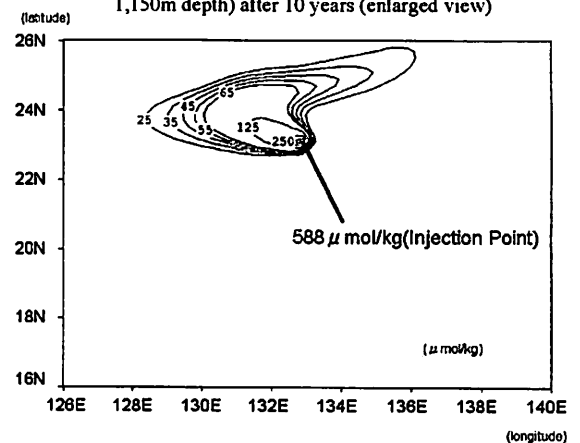


Fig.12 CO<sub>2</sub> concentrations with 0.2 degree square grid (Layer 10, 1,375m depth) after 10 years (enlarged view)

between the fixed point release method and the moving ship method. First, we investigated the fixed point release method. We performed the calculation for the case in which CO<sub>2</sub> was injected into the 10th layer continuously for 10 years and also for the case in which CO<sub>2</sub> was not released, and compared the results to determine the amount of CO<sub>2</sub> increase caused by oceanic storage. The difference between the results for both cases (the CO<sub>2</sub> concentration increase) is shown for only a coarse mesh in Fig. 9, and after the introduction of a fine mesh in Fig. 10. Enlarged views of the CO<sub>2</sub> concentration increase distribution are shown for the case of only a coarse mesh in Fig. 11, and after the introduction of a fine mesh in Fig. 12. The CO<sub>2</sub> diffused eastward from the injection point and its concentration decreased. At this time, a check of the flow in layer 10 revealed that the spread of CO<sub>2</sub> was affected by the flow field; there was practically no spread of CO<sub>2</sub> concentration toward the South Pacific Ocean. With only a coarse grid, the CO<sub>2</sub> was averaged within each 2degree by

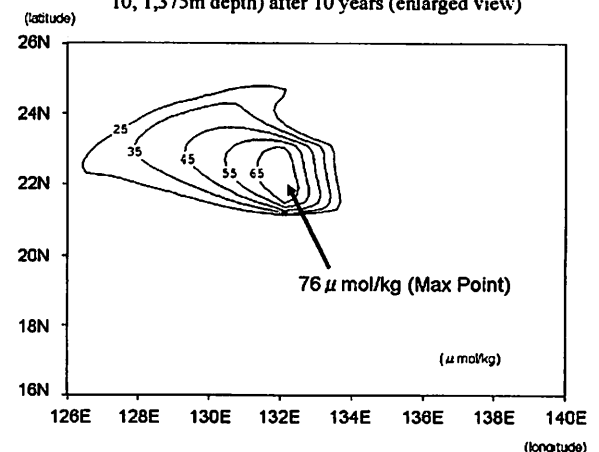


Fig.13 CO<sub>2</sub> concentrations calculated by moving ship method with 0.2 degree square grid (10 layers, 1,375m depth) after ten years (enlarged view)

2degree quadrangle to a value of only about 62μmol/kg; but with a fine mesh the concentration at the injection point increased to about 588μmol/kg.



Comparing Fig. 9 and Fig. 10, the region within which the CO<sub>2</sub> concentration increased within the range of 2 to 10 μmol/kg had a greater lateral spread with only a coarse grid. The region where the CO<sub>2</sub> concentration increased within the range of 2 to 0.5 μmol/kg was about the same in both cases. The region of increase 0.5 μmol/kg or less showed a greater spread with a fine grid added. This is believed to be because, compared to the case with only a coarse grid, when a fine grid is added the CO<sub>2</sub> concentration gradient is a larger in the vicinity of the injection point, causing the region with high concentration to be narrower; conversely, the region of low concentration spread out laterally.

Next, an enlarged diagram of the CO<sub>2</sub> increase distribution after introduction of the fine grid, as determined by the moving ship method, is shown in Fig. 13. From this it is seen that the point at which the increase of concentration is greatest lies about in the middle of the ship's range of movement; the concentration at that point is about 76 μmol/kg. Comparing Fig. 12 and Fig. 13, CO<sub>2</sub> is affected by the flow; it first spreads toward the west, then toward the northeast. From this fact, it is inferred that the moving ship method itself depends on the effect of the flow. In the present research, the CO<sub>2</sub> was injected over an area 100 times larger in the moving ship method than in the fixed point method, while the maximum concentration was about 1/8 that in the fixed point method. This shows clearly that the area over which low concentration is distributed is much larger than in the case of the fixed point method.

## 5. THE EFFECT OF THE INJECTED CO<sub>2</sub> ON LIVING ORGANISMS

The effect of oceanic storage of CO<sub>2</sub> on living organisms was evaluated by collecting existing information on the effect of CO<sub>2</sub> on living organisms and applying that knowledge to the calculated results given in Section 3-3 (Fig. 12, Fig. 13). It is believed that when CO<sub>2</sub> is injected into the ocean, organisms are affected via lowering of the pH of sea water. We expected that injecting CO<sub>2</sub> into the 10th layer (at 1,375m) would be effective in diluting it, but at present there is little knowledge about the effect of exposure to CO<sub>2</sub> on organisms in the intermediate and deep layers. For this reason, in the present research we have conducted the evaluation by applying the results of Kikkawa et al.<sup>25), 26)</sup> and Kurihara et al.<sup>27), 28)</sup> from experiments on the effect of exposure of shallow sea fishes to CO<sub>2</sub>.

Kikkawa et al.<sup>25), 26)</sup> studied the effect of exposure to CO<sub>2</sub> on the eggs and fry of several fish species. They reported that the normal hatching rate for sea bream dropped to 0 when the pH fell to 6.55; while

when the pH fell further, to 6.16, the survival rate of fry already hatched also dropped to 0. They also reported that in an experiment on sand borers, when the pH was 7.32±0.04, the growth rate fell to 10% of that under normal conditions (of no exposure to CO<sub>2</sub>). Here, "normal hatching rate" refers to the proportion of individuals that hatch not counting any that are malformed or premature. "Survival rate" refers to the number of individuals that survive in any condition at all.

Kurihara et al.<sup>27), 28)</sup> conducted CO<sub>2</sub> exposure experiments on the survival rate of female copepod plankton (*Acartia steueri* and *Acartia erithraea*) and on the normal hatching of 2 species of sea urchin (*Hemicentrotus pulcherrimus* and *Echinometra mathaei*). According to their results, the survival rate of *A. steueri* after 6 days at pH 7.55 was 50% compared to a survival rate for the control group with no CO<sub>2</sub> storage of 70%; the survival rate of *A. erithraea* after 8 days at pH 7.08 was about 50% compared to the control group survival rate of 60%. As for the number of eggs laid, the *A. steueri* control group laid 25 eggs after 6 days, compared to 20 at pH 7.55 and 1 at pH 7.02. The corresponding figures for *A. erithraea* are reported to be 58 for the control, 48 at pH 7.08 and 22 at pH 6.96.

Next, from the results of CO<sub>2</sub> exposure tests on fertilized sea urchin eggs, it has been reported that for *H. pulcherrimus* an effect is seen at pH 7.5; at pH 6.83 the normal hatching rate drops to about 50%. For *E. mathaei* an effect is seen at pH 7.6; at pH 6.79 the normal hatching rate drops to 10% or less.

The results of CO<sub>2</sub> concentration calculation show that the concentration increases in the vicinity of the injection point, so the pH distribution in the 10th layer in the vicinity of the injection point was calculated, and the effect on marine organisms were investigated (Fig. 14, Fig. 15). The pH was calculated from the following equation.

$$pH = -\log a_H \quad (10)$$

Here,  $a_H$  is the activity of the hydrogen ion concentration. This is a type of hydrogen ion concentration to correct the errors that exist in ideal systems and real systems.  $a_H$  is computed from the CO<sub>2</sub> concentration, water temperature, salinity and alkalinity<sup>11)</sup>.

Results of calculations done according to the fixed point release method show that the minimum pH occurs at the injection point, where the pH is 7.47 or less (Fig. 14). From Fig. 14, it can also be inferred that major reduction of pH occurs within several tens of kilometers of the injection point. Results of calculations done by the moving ship method show

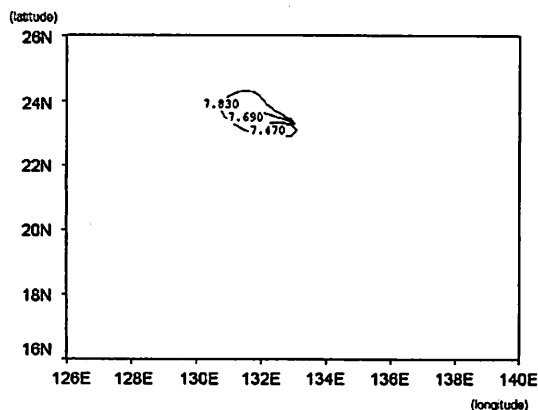


Fig.14 pH concentrations (Layer 10, 1,375m depth) after ten years using the fixed point method

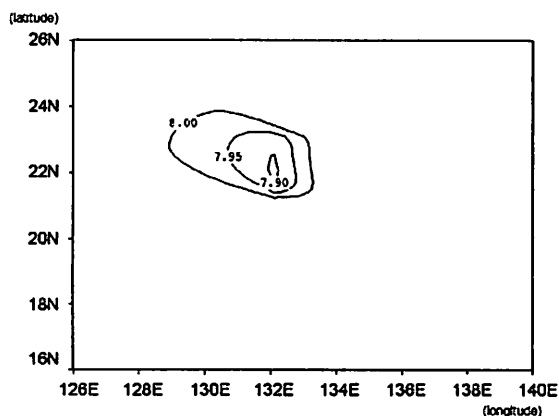


Fig.15 pH concentrations (Layer 10, 1,375m depth) after ten years calculated from a moving ship method

that the minimum pH occurs at the injection point in that case as well, with a value of 7.89.

The reduced values of pH calculated by both the fixed point release method and the moving ship method are approximately the same values for which significant biological effects were reported by Kikkawa et al.<sup>25),26)</sup> and by Kurihara et al.<sup>27),28)</sup>. These results indicate clearly that in order to evaluate the biological effects of the amount of CO<sub>2</sub> injection, a model resolution of 0.2degree by 0.2degree is necessary.

## 6. SUMMARY

In this research, we have focused on oceanic storage of CO<sub>2</sub>, which is one of the technologies for suppressing increase of the amount of CO<sub>2</sub>, believed to be the principal cause of global warming, in the atmosphere. We have used a model that considers the processes that govern the carbon cycle in the ocean, including the oceanic general circulation, the exchange of CO<sub>2</sub> between atmosphere and ocean, and

the biological pump. We used this model to predict the CO<sub>2</sub> concentration and to evaluate the biological impact of the increase in CO<sub>2</sub> concentration. We found that in order to achieve these objectives, the existing model (horizontal resolution 2degree by 2degree, 11 layers in the vertical) needed to be improved by introducing a finer grid (horizontal resolution 0.2degree by 0.2degree, 16 layers in the vertical).

1) As the first step in this research, we attempted to improve the accuracy of reproduction of the detailed flow field and of prediction of the CO<sub>2</sub> concentration by introducing a fine grid over part of the region covered. As regards the flow field, it was confirmed that there is a clockwise flow within the area covered by the fine grid. From 134 ° E to 140 ° E, along 25 ° N, a large difference was found in the current speed before and after introduction of the fine grid. In the deep layer, a flow along the bottom contours was found after the fine grid was introduced. Using this flow, oceanic storage of CO<sub>2</sub> was simulated, and investigations relating to the CO<sub>2</sub> injection depth were carried out. The results suggested that the 10th layer (1,250m to 1,500m) would be a favorable depth at which to inject the CO<sub>2</sub> because practically no CO<sub>2</sub> reaches either the ocean surface or bottom, and also because it is a favorable depth from the point of view of cost.

2) Based on these results, CO<sub>2</sub> concentrations were predicted for both the fixed point release method and the moving ship method. With only a coarse 2degree by 2degree grid, the predicted concentration is about 60μ mol/kg; after the fine grid was introduced, this increased to 588μ mol/kg, with a larger gradient of concentration. Different concentration increases were seen with the fixed point release method and the moving ship method, even with the same load. With the fixed point release method, the concentration increase at the injection point is large; with the moving ship method, the increase along the injection path is not so large but a smaller increase occurs over a wider area. The maximum increase in the case of the moving ship method occurs at about the center of the navigation path.

3) Next, we computed the pH produced by the increased CO<sub>2</sub> concentration and compared the resulting effect on marine organisms with that known from previous research. As a result, it was found that with the moving ship method, the increase of concentration occurred over a wider area, but the decrease in concentration was large, and the decrease in pH occurred over a narrower area than with the fixed point release method. This suggests a possibility that the moving ship method might result in a reduced effect of increased CO<sub>2</sub> concentration on marine organisms as compared to the fixed point

release method.

## ACKNOWLEDGMENT

The authors are grateful to Dr. S. Nagoya and M. Takahashi of Ark Information System for their valuable assistance in the computational work.

This work was supported by grant from Nihon University, Advanced Research Institute for the Science and Humanities.

## REFERENCES

- 1) Wada, A. : Marine Environment Hydraulics, Maruzen CO. LTD., 2007. (in Japanese)
- 2) Nakashiki, N., and T. Hikita : OCEAN INTERMEDIATE DEPTH INJECTION, *Energy Convers. Mgmt.*, Vol. 36, No. 6-9, pp. 453-456, 1995.
- 3) Tejima, T., T. Kamei, T. Sato : Structure of vortices shedding from an inclined cylinder, *CFD*, 2003. (in Japanese)
- 4) Masuda, Y., Y. Yamanaka, Y. Sasai, M. Magi, and T. Ohsumi : A numerical study with an eddy-resolving model to evaluate chronic impacts in CO<sub>2</sub> ocean sequestration, *Jour. of Greenhouse Gas Control*, Vol. 2, pp. 89-94, 2008.
- 5) Sorai M., T. Ohsumi : Ocean uptake potential for carbon dioxide sequestration, *Geochemical Journal*, Vol. 39, pp. 26-45, 2005.
- 6) Hasegawa, K., A. Wada, R. Nishimura and K. Takano : Prediction of CO<sub>2</sub> concentration caused by CO<sub>2</sub> introduction into the North Pacific Subarctic regions, *Jour. of The Japan Society for Marine Surveys and Technology*, Vol. 28, pp. 13-28, 2002. (in Japanese)
- 7) Nakamura, T., A. Wada, K. Hasegawa and M. Ochiai : A concentration prediction in CO<sub>2</sub> ocean isolation in the Japanese sea near the shore and influence to marine animals, *Jour. of Hydraulic Engineering*, Vol. 51, pp. 1475-1480, 2007. (in Japanese)
- 8) Hasegawa, K., A. Wada, R. Nishimura and K. Takano : Calculations of the concentration of radionuclides (Cs-137, Sr-90, Pu-239/240) in the Pacific Ocean, *Jour. of Hydrosience and Hydraulic Engineering*, Vol. 20, No. 2, pp. 277-237, 2002.
- 9) Nagoya, S. : A Method of Projection into Solenoidal Space for Incompressible Fluid Dynamics, *The Japan Society for Industrial and Applied Mathematics*, Vol. 10, pp. 273-282, 2000. (in Japanese)
- 10) Igarashi, H., A. Kameari, Y. Kagawa, I. Nishiguchi and A. Bossavit : Engineering and Mathematical Fundamentals in Computational Electromagnetism, *Baifukan Co. LTD.*, 2003. (in Japanese)
- 11) Berger, W. H. : Ocean Productivity and Paleoproductivity, *An Overview Productivity of the Ocean*, pp. 429-455, 1957.
- 12) Suzuki, A. : Seawater CO<sub>2</sub> system and its transformation caused by photosynthesis and calcification in coral reefs. -theory and measurements of reef metabolisms -, *Bull. Geol. Surv. Japan*, Vol. 45, No. 10, pp. 573-623, 16figs., 11tables, 1994. (in Japanese)
- 13) Tans, P. P., I.Y.Fung and T. Takahashi : Observational constraints on the global Atmospheric CO<sub>2</sub> budget, *Science*, Vol. 247, pp. 1431-1438, 1990.
- 14) Nojiri, Y. : NIES RESEARCH BOOKLET, No. 6, 2002. (in Japanese)
- 15) Takahashi, T., S. C. Sutherland, C. Sweeney, A. Poissonb, N. Metzlb, B. Tilbrook, N. Batesd, R. Wanninkhofe, R.A. Feelyf, C. Sabinef, J. Olafsson and Y. Nojiri : Global sea-air CO<sub>2</sub> flux based on climatological surface ocean pCO<sub>2</sub>, and seasonal biological and temperature effects, *Deep-Sea Research*, Vol. II, No.49, pp. 1601-1622, 2002.
- 16) Handa, Nobuhiro : Global warming, An approach from the atmospheric- hydrospheric science, *University of Nagoya Press*, pp. 271-286, 1996. (in Japanese)
- 17) Yamanaka, Y. : Modeling of Biogeochemical Cycles in the Ocean, *Tenki*, Vol. 44, pp. 835-845, 1994. (in Japanese)
- 18) Nozaki, Y. : Global Warming and the Oceans -The Role of Carbon cycling-, *University of Tokyo Press*, 1993. (in Japanese)
- 19) Eppley, R.W, Pererson, B.J. : Particulate organic matter flux and planktonic new production in the deep ocean, *Nature*, No.282, pp. 677-680, 1979.
- 20) Ozaki, M. : Technical feasibility of CO<sub>2</sub> Ocean sequestration, *Nippon Suisan Gakkaishi*, Vol. 64, No. 3, pp. 749-750, 2001. (in Japanese)
- 21) Ozaki, M. : CO<sub>2</sub> ocean storage and sequestration technology to ocean, *Gekkan Kaiyo*, Vol. 39, No. 6, pp. 361-366, 2007. (in Japanese)
- 22) Annual Report on the Environment in Japan, 2006. (in Japanese)
- 23) Chen-Tung A. Chen, Ricardo M. Pytkowicz : On the total CO<sub>2</sub> -titration alkalinity- oxygen system in the Pacific Ocean, *Nature*, Vol. 281, pp. 362-365, 1979.
- 24) Ohsumi, T., N. Nakashiki, K. Shitashima and K. Hiram : Density change of water due to dissolution of carbon dioxide and near-field behavior of CO<sub>2</sub> from a source on deep-sea floor, *Energy Convers. Mgmt.*, Vol. 33, No. 5-8, pp. 685-690, 1992.
- 25) Kikkawa, T., A. Ishimatsu and J. Kita : Acute CO<sub>2</sub> tolerance during the early developmental stage of four marine teleosts, *Environmental Toxicology*, Vol. 18, pp. 375-382, 2003.
- 26) Kikkawa, T., T. Sato, J. Kita and A. Ishimatsu : Acute toxicity of temporally varying seawater CO<sub>2</sub> conditions on juveniles Japanese sillago, *Marine Pollution Bulletin*, Vol. 52, pp. 621-625, 2006.
- 27) Kurihara, H., S. Shimode, and Y. Shirayama : Effects of raised CO<sub>2</sub> concentration on the egg production rate and early development of two marine copepods, *Marine Pollution Bulletin*, Vol. 49, pp. 721-727, 2004a.
- 28) Kurihara H, and Y Shirayama : Effects of increased atmospheric CO<sub>2</sub> on sea urchin early development, *MARINE ECOLOGY PROGRESS SERIES*, Vol. 274, pp. 161-169, 2004b.

(Accepted in Japanese for Journal of the Japan Society for Marine Surveys and Technology, Vol.21, No.21, pp.1-13, September,2009)

(Received in English for JGEE, September 29, 2009)

(Accepted in English for JGEE, January 23, 2010)