Optimization of the horizontal shape of CO₂ injected domain and the depths of release in moving-ship type CO₂ ocean sequestration

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Abstract In moving-ship type CO₂ ocean sequestration, liquid CO₂ is discharged into a domain in a water column. Since the maximum CO₂ concentration that is reached depends on the horizontal shape of the water column and the depths of release, it is very important to optimize these parameters for each injection site in order to minimize the biological impact. We conducted numerical experiments using an offline Oceanic General Circulation Model with a horizontal resolution of 0.1 degree x 0.1 degree. Experiments using a different horizontal site shape show that a site elongated in the meridional direction is effective to reduce the CO₂ concentration. This is because CO₂ has a tendency to be transported in a zonal direction. Optimization of the vertical distribution of CO₂ injections is inherently determined by the balance of the following two factors; (1) dilution effect by eddy activity which decreases with depth, and the (2) predicted no effect concentration (PNEC), a criterion concentration causing no effect on biota, which increases with depth. Based on superposition of simulated CO₂ concentration, we determined the optimized vertical distribution of CO₂ injection which keeps the ratio of a simulated maximum CO₂ concentration to PNEC constant.

Keywords CO₂ ocean sequestration · Carbon dioxide capture and storage (CCS) · Injection site · Biological impacts · PNEC

1 Introduction

CO₂ ocean sequestration has been proposed as an effective strategy to mitigate global warming [1]. In the moving ship method [2, 3], liquid CO₂ is discharged into the mid-depth ocean from a suspended conduit. Figure 1 presents a sketch of the moving ship concept. CO₂ is discharged within a site which is a domain in a water column within a few degrees of the horizontal. The released CO₂ forms droplets that slightly ascend due to buoyancy and dissolve into the surrounding water [4–6]. CO₂-enriched seawater is advected by currents from the injection site and diffuses into the surrounding water [7–9]. If the CO₂ concentration is decreased sufficiently by dilution, then the biological impacts are expected to be small. At time scales greater than a few months, related biological impacts are not acute but chronic. In an earlier numerical study, consecutive CO₂ injections were found to cause an increase in the CO₂ concentration during the first several to 10 years which eventually reaches an upper limit [10]. A biological study proposed an index that identifies no effect on biota, which is called predicted no effect concentration (PNEC) [11]. Results of many biological experiments [12] are used to estimate PNEC. The PNEC is defined as the highest CO₂ concentration which causes no effects on the weakest species divided by assessment factors with various uncertainties taken into

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The second objective is to optimize the vertical distribution of injected CO₂. Initial vertical distribution of injected CO₂ is determined by injection depths and sizes of droplets. Therefore, to optimize the vertical distribution gives important information regarding injection depths and sizes of droplets in order to avoid chronic impacts on biota. In previous numerical studies where the vertical distributions of injected CO₂ are pre-determined, the maximum CO₂ concentration is close to PNEC around 1700 m while it is far smaller than PNEC at some other depths [14]. The objective of the optimization is to keep the ratio of the maximum CO₂ concentration to PNEC constant. If so, we can inject the maximum amount of CO₂ as the maximum concentration correspondent with PNEC, or the maximum concentrations have the same margin to PNEC at all depths. The optimized vertical distribution of injected CO₂ is considered to be determined by the balance of the following two factors. PNEC increases with depth where CO₂ injection is implemented. However, eddy activity which works to effectively dilute CO₂ becomes smaller with depth increasing [10].

2 Model and design of experiments

2.1 Model

CO₂ concentration is calculated by an offline model with a horizontal resolution of 0.1 degree × 0.1 degree. The offline model is based on the Coupled Ocean-Sea-Ice Model for the Earth Simulator (OIFES) developed at the Earth Simulator Center/Japan Agency for Marine-Earth Science and Technology (JAMSTEC) [17, 18]. The model has 54 vertical layers with realistic geometry. Horizontal and vertical velocities are not calculated in the offline model but daily-mean velocities calculated in OIFES (online model) applied in the North Pacific are used. We conducted a simulation for 30 years and the daily-mean velocities during 5 years are repeated six times. The integration during 30 years is considered to be sufficient long to simulate the maximum concentration of CO₂, since previous numerical results showed that CO₂ concentration nearly reaches its upper limit within 10 years from the beginning of the injection [10]. The domain of the offline model is 120°E–180°E, 10°N–50°N. Since the model has open lateral boundaries, the total amount of the injected CO₂ is not accurately conserved. However, a previous study using the online model applied in the North Pacific (98°E–70°W, 20°S–68°N) confirmed that almost all of the injected CO₂ remains in the domain for 30 years if CO₂ is injected in Japanese waters [15]. We treated CO₂ as a purely passive tracer dissolved in seawater. Since we simulated CO₂ transport and dilution on
a time scale longer than several weeks after the initial dilution processes are completed, including dissolution of droplets and plume dynamics, we assumed that the CO₂ concentration is low enough not to cause vertical movement due to density differences. A liquid droplet-plume model showed that a vertical movement of seawater due to density difference does not occur if the CO₂ concentration is lower than 0.02–0.03 kg/m³ [4]. Since the maximum CO₂ concentration is estimated to be about 0.002 kg/m³ in our previous study [14], vertical movement does not occur. Our model does not express subgrid phenomena, which would be potential sources of error. We cannot directly validate our simulation for ocean sequestration, but it is encouraging that the simulation of chlorofluorocarbon using the same model agrees well with the observations [19].

2.2 Experiments to optimize the horizontal shape of a site

To assess effects of the horizontal shape of a site on CO₂ concentration, three CO₂ injection experiments were conducted in addition to Exp. H1x3 in a previous study [14], in which CO₂ is injected in a site of 1 degree in longitude and 3 degrees in latitude (Table 1). The ocean area around the site has been studied for many years by the research project for CO₂ sequestration managed by the Research Institute of Innovative Technology for the Earth, and physical, chemical and biological data have been accumulated. In Exp. H3x1 and H1x2, we used sites of 3 degrees in longitude and 1 degree in latitude, and 1 degree in longitude and 2 degrees in latitude, respectively. In Exp. H1x1_2, CO₂ is injected simultaneously into two sites of 1 degree × 1 degree at a 1 degree interval of latitude. By the experiments, effects of site area and shape on CO₂ concentration are examined. Comparing H1x3 and H3x1, we examine the concept that a site extended in latitude is more effective to dilute the CO₂ concentration. In all the experiments, CO₂ is consecutively injected at a rate of 50 Mton/year. Note that CO₂ injection rate per unit volume is larger in H1x2 and H1x1_2 than in H1x3 and H3x1, where 50 Mton/year CO₂ is injected into the area of 2 degrees² in the former and 3 degrees² in the latter. While CO₂ injection is uniform on a horizontal plane, it depends on depth.

| Exp.   | Site location          | Injection depth (m) | Injection flux (Mton/year) | Injection rate per volume (ppm/year) |
|--------|------------------------|---------------------|---------------------------|-------------------------------------|
| H1x3   | 133°–134°E, 19°–22°N   | 977–2719            | 50                        | 0.077–1.45                          |
| H3x1   | 132°–135°E, 20°–21°N   | 977–2719            | 50                        | 0.077–1.45                          |
| H1x2   | 133°–134°E, 19.5°–21.5°N | 977–2719         | 50                        | 0.116–2.18                          |
| H1x1_2 | 133°–134°E, 19°–20°N   | 977–2719            | 50                        | 0.116–2.18                          |

V1  133°–134°E, 19°–22°N  977–1113  4.86  1.0
V2  133°–134°E, 19°–22°N  1113–1264  5.37  1.0
V3  133°–134°E, 19°–22°N  1264–1429  5.88  1.0
V4  133°–134°E, 19°–22°N  1429–1609  6.40  1.0
V5  133°–134°E, 19°–22°N  1609–1803  6.91  1.0
V6  133°–134°E, 19°–22°N  1803–2012  7.42  1.0
V7  133°–134°E, 19°–22°N  2012–2234  7.92  1.0
V8  133°–134°E, 19°–22°N  2234–2470  8.40  1.0

Fig. 2 Vertical distribution of injected CO₂ in Exp. H3x1, H1x3, H1x2, and H1x1_2.
vertical distribution of the injected CO$_2$ is shown in Fig. 2 [20]. This is obtained based on results of two liquid droplet models [21, 22] under the following assumptions: the same amount of CO$_2$ is injected from pipes at depths of 2500, 2290, 2080, 1970, 1830 and 1640 m, and CO$_2$ droplet size is 14 mm.

2.3 Experiments to optimize vertical distribution of injected-CO$_2$ amount

Our model has eight layers in 977–2470 m in which CO$_2$ is assumed to be injected. Corresponding to the eight layers, we conducted eight experiments V1–V8 in which CO$_2$ is injected into only one layer. Horizontal shape of a site is the same as that of H1x3, since the shape of H1x3 has an advantage to dilute CO$_2$ effectively, as shown later. CO$_2$ injection flux per unit volume is 1.0 ppm/year, which is common in V1–V8. Since the CO$_2$ equation is linear, superposition of the simulated CO$_2$ concentrations multiplied by a constant also satisfies the equation for CO$_2$ concentration. If a set of the constants is properly selected, we can keep the ratio of a maximum CO$_2$ concentration to PNEC constant through the CO$_2$-injected layers from 977 to 2470 m.

3 Results

3.1 Experiments to optimize the horizontal shape of a site

After 30 years from the beginning of the CO$_2$ injection, CO$_2$ extends a thousand kilometers in H1x3, H3x1, H1x2 and H1x1_2 (Fig. 3). Most of the CO$_2$-dissolved water is transported in a zonal direction, as in the previous study [14]. Relatively high CO$_2$ concentration is obtained around the injection sites. The maximum concentration at 1904 m is higher in H1x2 and H3x1 than in H1x3 and H1x1_2. For each model layer, we calculated the maximum CO$_2$ concentration during 30 years, and compared it to PNEC.

![Fig. 3 Horizontal distributions of monthly mean CO$_2$ concentration at 1904 m after 30 years from the beginning of the injection in Exp. a H1x3, b H3x1, c H1x2, and d H1x1_2](image-url)
would be resulting from the smaller amount of the overlap in H1x1_2 than in H1x2. The maximum CO₂ concentration in H1x1_2 is slightly higher than that in H1x3, and the maximum in H1x1_2 is achieved at a depth where PNEC is relatively small. As a result, the ratio of the maximum concentration to PNEC is larger in H1x1_2 than in H1x3. Therefore, we conclude that the site in H1x3 is the optimal horizontal shape of the four experiments.

3.2 Experiments to optimize the vertical distribution of injected-CO₂

Vertical distribution of injected CO₂ was optimized, using the results of the experiments V1–V8. The distributions of CO₂ concentration at CO₂-injected depth after 30 years from the beginning of the injection are shown in V1, V4, V6 and V8 (Fig. 5). CO₂ concentration increases with depth, since dilution of CO₂ by mesoscale eddies decreases with depth. Relatively large CO₂ concentrations occur around the injection sites. We calculated the maximum concentration for each model layer in every experiment (Fig. 6). The maximum concentrations at different layers do not necessarily occur simultaneously. The maximum CO₂ concentration increases as CO₂-injected depth increases, where CO₂ injection flux per unit volume is the same in V1–V8. The distribution of the maximum concentrations takes a peak at the CO₂-injected layer. In many cases, the CO₂ concentration in layers below the CO₂-injected layer is larger than that in upper layers, where the CO₂ concentration in layers below the CO₂-injected layer is caused by vertical advection and diffusion of CO₂-enriched seawater.

To optimize the vertical injection amount, we considered the following equation:

\[
\begin{pmatrix}
    a_{V1,1} & a_{V2,1} & \cdots & a_{V8,1} \\
    a_{V1,2} & a_{V2,2} & \cdots & a_{V8,2} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{V1,8} & a_{V2,8} & \cdots & a_{V8,8}
\end{pmatrix}
\begin{pmatrix}
    x_1 \\
    x_2 \\
    \vdots \\
    x_8
\end{pmatrix}
= 
\begin{pmatrix}
    c_1 \\
    c_2 \\
    \vdots \\
    c_8
\end{pmatrix}
\]

where \( a_{ij} \) shows the maximum concentration obtained in Fig. 6a, and the first and second indexes denote the experiments and model layer, respectively. For example, \( a_{V1,1} \) is the maximum concentration in V1 at the uppermost layer (977–1113 m) in the CO₂-injected layers in V1–V8. In the equation, \( c_1 - c_8 \) show PNEC at the model layers, and \( x_1 - x_8 \) are coefficients to be solved, which give an optimized CO₂ injection flux. If the coefficients are properly given, we can keep the ratio of maximum concentration to PNEC 1.0 through all the model layers in which CO₂ is injected in V1–V8. The CO₂ concentration above (≤977 m) and below (>2470 m) the CO₂-injected layer are small and are ignored in the estimation. Note that this is a conservative
estimation since the maximum concentration $a_{ij}$ in Eq. 1 do not necessarily occur simultaneously. Since the Eq. 1 is linear, the following equation is also obtained:

$$\begin{bmatrix} a_{V1,1} & a_{V2,1} & \cdots & a_{V8,1} \\ a_{V1,2} & a_{V2,2} & \cdots & a_{V8,2} \\ \vdots & \vdots & \vdots & \vdots \\ a_{V1,8} & a_{V2,8} & \cdots & a_{V8,8} \end{bmatrix} \begin{bmatrix} \alpha x_1 \\ \alpha x_2 \\ \vdots \\ \alpha x_8 \end{bmatrix} = \begin{bmatrix} \alpha c_1 \\ \alpha c_2 \\ \vdots \\ \alpha c_8 \end{bmatrix},$$

(2)

where $\alpha$ is the reciprocal of a safety factor. The positive constant $\alpha$ takes a value less than 1.0. Once $x_1 \sim x_8$ are calculated, corresponding to an arbitrary safety factor we can easily estimate the CO$_2$ injection flux which keeps the ratio of maximum concentration to PNEC $\alpha$ through the eight model layers.

The calculated $x_1 \sim x_8$ values are shown in Fig. 7. At the each of the model layers, if we inject a CO$_2$ flux of 1.0 ppm/year times the coefficients $x_j$, the estimated maximum CO$_2$ concentration will be the same as PNEC. Without causing CO$_2$ larger than PNEC, up to 86.7 Mton CO$_2$/year ($\sum_{j=1}^{8} x_j V_j \rho$) can be injected, where $V_j$ is the volume of the each model layer, and $\rho$ is seawater density. Note that this value will be revised if PNEC is refined based on results of future biological experiments. We can inject relatively larger CO$_2$ in the upper layer than in the deeper layer without causing CO$_2$ concentration larger than PNEC. As shown above, PNEC increases with depth where CO$_2$ injection is implemented, but eddy activity diluting CO$_2$ concentration becomes small with depth. In the optimization of CO$_2$ injection flux, the effect of the latter is larger than that of the former.

4 Summary and discussion

In moving-ship type CO$_2$ ocean sequestration, liquid CO$_2$ is discharged into a domain in a water column. Since the maximum CO$_2$ concentration that is reached depends on the horizontal shape of the water column and the depths of release, it is very important to optimize these parameters for each injection site in order to minimize biological impact. To simulate CO$_2$ concentration, we used an offline
model based on OIFES with a horizontal resolution of 0.1 degree × 0.1 degree. Simulated maximum CO₂ concentration is compared with PNEC which is an index causing no effect on biota. To optimize the horizontal shape of an injection site, we conducted experiments in which CO₂-injected sites have a different horizontal shape. Comparing the two experiments in which the injection sites are of 1(lon) × 3(lat) and 3(lon) × 1(lat) degree, we showed that a site extended in a meridional direction is effective to dilute injected CO₂. This is because CO₂ has a tendency to be transported in a zonal direction. The experiment with the two sites at 1 degree intervals in latitude showed that the meridional interval is effective to decrease CO₂ concentration. The experiment shows the possibility that we can set some sites around Japan without increasing the concentration of CO₂ over PNEC. If we can set multiple sites without causing biological impacts, it enables us to sequester huge amounts of CO₂ into the ocean.

Fig. 6 Maximum CO₂ concentration at each layer simulated in Exp. a V1, b V2, c V3, e V4, f V5, g, V6, and h V8. The maximum concentration is calculated within 1 degree from the site (132°E–135°E, 18°N–23°N)
To optimize the vertical distribution of CO2 injection, we conducted eight experiments in which CO2 is injected into only one layer of eight layers from 977 to 2470 m. Since the equation for CO2 concentration is linear, superposition of the simulated CO2 concentrations multiplied by a constant also satisfies the equation for CO2 concentration. We estimated the constants which keep the ratio of a maximum CO2 concentration to PNEC constant through the CO2-injected layers. The estimated constants which show possible injection flux without biological impacts are relatively larger CO2 in upper layers than in deeper layers. In the two important factors affecting biological impacts, PNEC increases with depth where CO2 injection is implemented, but eddy activity diluting CO2 concentration becomes small with depth. The result of the estimation shows that the effect of the latter is larger than the former. In a real ship operation, vertical distribution of CO2 injection flux results from dissolution of CO2 liquid droplets into the surrounding water. We need to design the proper length of injection pipes, CO2 droplet sizes and CO2 injection flux from pipes, as the resultant vertical distribution of CO2-injection flux is close to that estimated in the paper. This is beyond the scope of the paper and will be explored by a modeling team using liquid-droplet models in future.

In the above optimization, we focused on one site located southeast of Japan. Optimization in other sites is discussed below. A previous study [15] in which CO2 is injected in several sites in different ocean areas showed that most of the CO2-dissolved water is transported in the zonal direction. Therefore, a site extended in a zonal direction would be effective to dilute CO2 concentration in a wide ocean area. Optimized vertical distribution of injection flux will be considerably different among sites, since eddy activity differs by a factor of 10 in different ocean areas [15]. However, the optimizing method presented in the paper is also applicable.

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