EFFECTS OF VERTICAL DIC DISTRIBUTION ON STORAGE EFFICIENCY OF DIRECT INJECTION OF CO_2 INTO THE OCEAN

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ABSTRACT
We estimated the effects of initial vertical distribution of dissolved inorganic carbon (DIC) on storage efficiency of direct injection of CO_2 into the ocean. Our simulations shown that the storage efficiencies could be reduced up to 10% if a relative large droplet (30 mm in diameter) was injected at depth of 1500m. The storage efficiency of CO_2 ocean sequestration is strongly related with not only injection depth but also the initial CO_2 droplet diameter. With a given injection rate, the larger droplets injected will produce a dilute DIC plume and thus improve the acute biological impacts but a smaller storage effective due to droplet ascending.

INTRODUCTION
CO_2 ocean sequestration had been studied as a mean to mitigate the accumulations of carbon dioxide in the atmosphere [*Marchetti*, 1977], To assess this technology, simulations, using either ocean general circulation models [OGCMs, *Caldeira et al.,* 2002] or one-dimensional diffusion models (Herzog et al., 2003), predicted that the sequestration efficiency is strongly related with the injection depth. These simulations simply set the initial dissolved inorganic carbon (DIC) concentration by release DIC at a fixed vertical layer given as the injection depth. In the engineering performance of CO_2 ocean sequestration, however, the buoyant CO_2 droplets can normally raise up, depending on the initial diameter, hundreds meters from release depth before completely dissolved. The rising droplets coupled with ocean current produce a CO_2 enriched seawater plume with a vertical concentration distribution. The dynamic structure of this plume is also the affected by injection rate, injection techniques employed, and the ocean turbulence. The roles of this near-filed dynamics on long-term CO_2 ocean storage are examined in this study. We performed numerical simulations in a two-phase-box and then the long-term storage efficiency data from a three dimensional ocean general circulation models are adopted to estimate the effects of initial vertical distribution of dissolved CO_2 on storage efficiency.

MODELS AND METHODS APPLIED
To estimate the initial vertical distribution of dissolved CO_2, a two-phase box model is developed. This is a modified version of the two-phase small-scale turbulent ocean model [*Chen et al.,* 2003]. This model focuses on droplet dynamics, including dissolution and vertical motion once the droplets were released from the nozzle. We adopted a Lagrangian framework to monitor these released droplets inside a seawater column. The vertical scale of the model is variable depending on the ascending height of the droplets. Because of dissolution, a CO_2-enriched seawater plume was created in this target water column, which is treated by scalar conservative transport equations. This seawater column along with the droplets moves with the ocean current (in Lagrangian scheme). The dynamics of the released CO_2 droplets, including dissolution and buoyant ascending, could be simulated by the dynamics of an individual droplet when we further assumed that the collision and collection among droplets was negligible.

With this model, dissolved CO_2 is calculated and then statistically treated to a mass probability density function (pdf) as a function of depth. This pdf describes the initial vertical distributions of dissolved CO_2. Because the time scale of droplet dissolution (τ_d) is smaller in orders than the calculation time step of ocean cycle model (τ_c), we simply used this distribution to weight to the long-term storage efficiency data from OGCMs, of which no initial-vertical distributions were considered, by equation:

$$\eta_C(t) = \int_0^1 \eta_{C0}(h,t) \cdot P[x(h)]dx \tag{1}$$

where: h is the depth of the ocean (m), t is the time (year), η_c is the storage efficiency with an initial vertical distribution (pdf), η_{co} is the storage efficiency without initial vertical distributions, and $P(x_{(h)})$ is the probability density function of DIC initial vertical distribution functioned as a normalized depth ($x_{(h)}$).

RESULTS AND CONCLUSIONS

The injection technique simulated here is the direct injection liquid CO_2 droplets into mid-deep-ocean by moving-ships. The model can handle injection parameters, such as CO_2 injection depth, rate, and initial droplet diameters, and injection site environments, such as seawater temperature, salinity, and currents. Simulations were run under sequestration scenarios described in the OCMIP protocols. CO_2 injection location is near the Tokyo at entire injection rate of 0.37 Gt CO_2 yr^{-1} for 100 years. The diameters of injected CO_2 droplet (*Do*) are range from 5 to 40 mm with a lognormal distribution. According to Equation 1, we estimated the effects of initial-vertical distributions on the storage efficiency. Fig. 1 shown an example of the case at injection depth of 2000m. It can be fined out that the storage efficiencies could be reduced range from 3% to 10% at elapsed time of 500 years when the vertical DIC distributions are considered. The larger droplets can rise up a long distance (800m for *Do*=40 mm) and then make more dissolved CO_2 reversed back to atmosphere early. To further estimate these vertical distribution effects, we examined the sensitivity to injection depths by:

$$S = 1.0 - \eta_c / \eta_{co} \quad (2)$$

As shown in Fig. 2., the sallower injection is more sensitive to the initial droplet size. The storage efficiency is even reduced by 17 % when *Do* = 20mm at injection depth of 1500m.

Consequently, our simulations suggested that the storage efficiency of CO_2 ocean sequestration is strongly related with not only injection depth but also the initial CO_2 droplet diameters. With a given injection rate, the larger droplets injected will produce a dilute DIC plume and thus improve the acute biological impacts but make the storage less effective. This effect should be taken when make assessment and accounting rules.

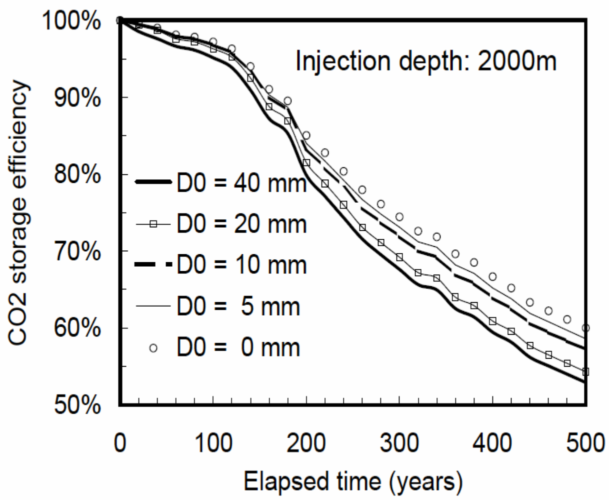

Fig.1. The effects of initial-vertical distribution of DIC on CO_2 storage efficiencies

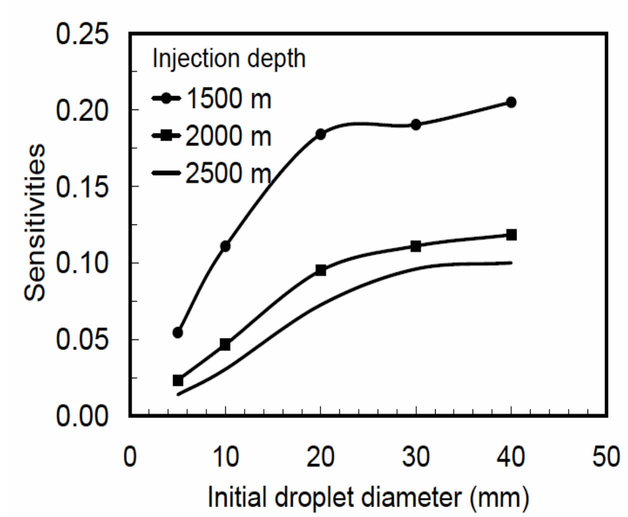

Fig.2. The effects of initial-vertical distribution of DIC to CO_2 storage efficiencies at variant injection depths.

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