

# Predicting and Evaluating the Effectiveness of Ocean Carbon Sequestration by Direct Injection

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# Predicting and evaluating the effectiveness of ocean carbon sequestration by direct injection

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## Abstract

Direct injection of CO<sub>2</sub> into the ocean is a potentially effective carbon sequestration strategy. Therefore, we want to understand the effectiveness of oceanic injection and develop the appropriate analytic framework to allow us to compare the effectiveness of this strategy with other carbon management options. Here, after a brief review of direct oceanic injection, we estimate the effectiveness of ocean carbon sequestration using one dimensional and three dimensional ocean models. We discuss a new measure of effectiveness of carbon sequestration in a leaky reservoir, which we denote *sequestration potential*. The sequestration potential is the fraction of *global warming cost* avoided by sequestration in a reservoir. We show how these measures apply to permanent sequestration and sequestration in leaky reservoirs, such as the oceans, terrestrial biosphere, and some geologic formations. Under the assumptions of a constant cost of carbon emission and a 4 % discount rate, injecting 900 m deep in the ocean avoids ~90 % of the global warming cost associated with atmospheric emission; an injection 1700 m deep would avoid > 99 % of the global warming cost. Hence, for discount rates in the range commonly used by commercial enterprises, oceanic direct injection may be nearly as economically effective as permanent sequestration at avoiding global warming costs.

## Introduction

Our society needs to understand the options available for controlling levels of atmospheric carbon dioxide, should the threat of CO<sub>2</sub>-induced harmful climate change prove real. If we wait until there is definitive proof of harmful climate change, it will be too late to develop large-scale solutions to the problem [Hoffert *et al.*, 1998].

The oceans contain approximately 50-fold more carbon than the atmosphere and already play an

important role in the storage of fossil-fuel carbon. About one-third of the carbon dioxide we emit (2 of 6 PgC/yr) is being absorbed by ocean surface waters and mixed to the deep ocean, with unknown long-term effects.

There are two major proposed strategies for ocean carbon sequestration:

- deliver CO<sub>2</sub> to deep waters by direct injection (avoiding climate effects and the biologically rich surface layer);

- increase the flux of organic carbon sinking to the deep waters by stimulating the natural biological pump in the surface ocean with the addition of nutrients.

Both strategies raise issues regarding environmental impacts, feasibility, and effectiveness. Sequestration strategies must not, in the long run, cause more environmental problems than they solve. Viable strategies must present tractable engineering problems and be able to make a real contribution to slowing the accumulation of CO<sub>2</sub> in the atmosphere.

CO<sub>2</sub> injection into the deep and intermediate ocean must be environmentally acceptable to the public at large. Even if the evidence indicates low risk, the public will need clear, complete information to understand its implications.

### Review of studies on direct carbon injection

Direct injection of CO<sub>2</sub> into the ocean interior has been proposed as an approach to slow the growth in atmospheric carbon dioxide content [Herzog *et al.*, in press]. The direct carbon injection concept was first mentioned by Marchetti [1977] who conceived of piping CO<sub>2</sub> into the outflow of the Mediterranean Sea, where it would sink deeper into the Atlantic. The idea of this approach is to inject fossil-fuel carbon dioxide into the ocean interior, thereby bypassing the slow mixing processes that would otherwise inhibit the transfer of excess atmospheric CO<sub>2</sub> into the ocean interior. For a specified energy demand scenario, direct injection of CO<sub>2</sub> in the ocean could slow CO<sub>2</sub> accumulation in the atmosphere, and thus global warming. However, this

would be at the expense of higher atmospheric CO<sub>2</sub> content in the distant future, due to the energy costs of injection [Kheshgi *et al.*, 1994].

Several methods for the direct injection of CO<sub>2</sub> into the ocean have been proposed:

- (1) injecting liquid CO<sub>2</sub> at a depth of ~1000 m from a manifold lying near the ocean bottom and forming a rising droplet plume [Liro *et al.*, 1992];
- (2) injecting liquid CO<sub>2</sub> at a depth of > 3000 m from a manifold near the ocean bottom and forming a sinking droplet plume;
- (3) creating a dense CO<sub>2</sub>-seawater mixture at a depth of between 500 and 1000 m forming a sinking bottom gravity current [Haugan and Drange, 1992];
- (4) releasing dry ice at the ocean surface from a ship [Nakashiki *et al.*, 1991];
- (5) injecting liquid CO<sub>2</sub> at a depth of about 1000 m from a pipe towed by a moving ship and forming a rising droplet plume [Ozaki *et al.*, 1995];
- (6) introducing liquid CO<sub>2</sub> to a sea floor depression forming a stable "deep lake" at a depth of about 4000 m [Ohsumi, 1995].

The evaluation of each scenario involves issues of environmental impact, sequestration efficiency, cost, and technical feasibility [Herzog *et al.*, 1995]. Options (1), (2), (5), and (6) have received most recent attention.

## Review of biotic impacts

The consequences of increasing CO<sub>2</sub> concentrations for marine biota are poorly understood. Work to try to fill in these gaps has begun at Monterey Bay Aquarium Research Institute (MBARI) [e.g., Tamburri *et al.*, 2000] and at other locations.

It has been widely recognized that the greatest impact from deep-sea CO<sub>2</sub> injection is likely to be a result of the change in deep-sea pH [Magnesen and Wahl, 1993]. It is important to note that the ocean is naturally sequestering anthropogenic carbon dioxide, and as the fossil-fuel reserves are burned, deep-sea pH is expected to decrease by as much as 0.5 pH units [Herzog *et al.*, 1995]. Magnesen and Wahl [1993] estimate that changes in ocean pH of more than 0.2 units will have some detectable biological impact. Rau and Caldeira [1999] and Caldeira and Rau [2000] have proposed using the dissolution of carbonate minerals to minimize the pH effects of adding CO<sub>2</sub> to the ocean.

Perhaps the most extensive modeling of the biological impacts of deep-sea CO<sub>2</sub> injection has been performed by the MIT Energy Laboratory [Caulfield, 1996; Adams and Herzog, 1996; Caulfield *et al.* 1997; Adams *et al.*, 1997]. These biological impacts are likely to be greatest in the near field, near the point of emission, but lesser impacts over a broader region of the ocean are also to be expected. Based on a number of biological studies, these authors developed an estimate of the mortality of marine organisms subjected to an exposure to low-pH waters for a specified amount of time. For a droplet plume scenario, these authors concluded that a typical power plant would produce on the order of 1 km<sup>3</sup> of water with pH

< 7. At this pH, many marine organisms may be relatively unaffected, but some species begin to show some signs of mortality. Nematodes and bacteria show drastic impacts only for pH less than 5.5 or 6 or less [Takeuchi *et al.*, 1997]. The volume of water with pH < 7 scales non-linearly with the amount of CO<sub>2</sub> emitted, such that diffuse and widely dispersed CO<sub>2</sub> emitters will minimize mortality. Because diapycnal diffusivity is far less efficient a transport mechanism than isopycnal diffusivity, expanding the vertical spacing of emission would likely be less expensive and more effective than increasing spacing in the horizontal direction.

Golomb *et al.* [1992] suggested that other impacts of deep-sea CO<sub>2</sub> disposal could include interference with feeding patterns of swimming creatures and burial of benthic organisms by CO<sub>2</sub>-hydrate on the sea floor. Golomb [1993] suggests that far-field effects of deep-sea injection are likely to be negligible. Around the injection hardware, ecosystems with enhanced biological activity are likely to form, such as those found around oil drilling platforms. It is less clear how marine organisms will respond to a stream of rising CO<sub>2</sub> droplets, however, marine biota have not shown great interest in rising CO<sub>2</sub> droplets observed during in-situ experiments [P. Brewer, personal communication, 1999]. Low pH could have direct effects on cell membranes or could cause conditions that will tend to erode calcareous components of marine organisms [Golomb, 1993].

Shirayama [1998] suggests that the long life span, low biological activity, high sensitivity to environmental disturbance, high species diversity, and low density of deep-sea organisms make them

potentially vulnerable to rather modest changes in ocean chemistry in ways that may be as yet unforeseen. Shirayama suggests that long-term *in situ* experiments can help us to develop a better understanding of the far-field biological and geochemical consequences of adding carbon to the ocean.

### Review of direct CO<sub>2</sub> injection simulations

Model simulations are used to estimate the effectiveness of direct CO<sub>2</sub> injection into the ocean (Figure 1). The large-scale effectiveness of direct CO<sub>2</sub> injection was first simulated by Hoffert *et al.* [1979]. Since that time, there have been several model-based studies of deep-injection of carbon dioxide using schematic ocean models [Flannery *et al.*, 1993; Kheshgi *et al.*, 1994; Cole *et al.* 1993; Wong and Mattear, 1993] and global ocean general circulation models [Xu *et al.*, 1999; Nakashiki and Ohsumi, 1997; Dewey *et al.*, 1997; Bacastow *et al.*, 1997; Stegen *et al.*, 1993]. These studies have indicated that deep injection of carbon dioxide could be an effective means of sequestering CO<sub>2</sub> in the oceans for hundreds of years or more.

In a comparison of simulated CO<sub>2</sub> injection near Tokyo and New York City, the model of Dewey *et al.* [1997] found that injection off New York would be more effective than injection off Tokyo; however, results at LLNL (Figure 2) and from other groups [J. Orr, personal communication, 1999] indicate the reverse. The fact that the results of these models are contradictory indicates the need for improved model development and evaluation, and performing simulations in a variety of models.

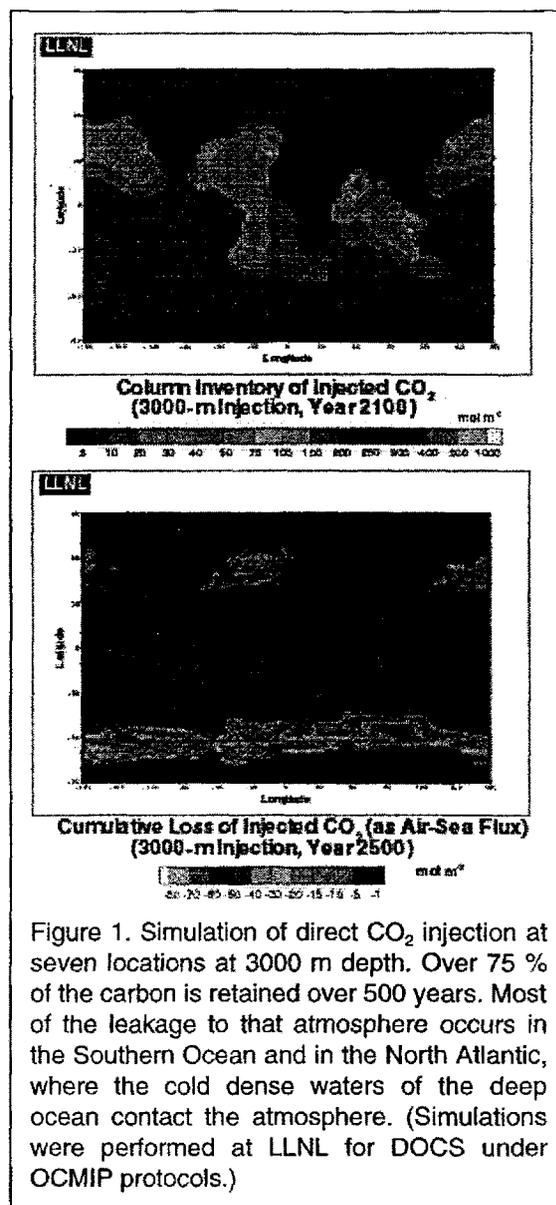


Figure 1. Simulation of direct CO<sub>2</sub> injection at seven locations at 3000 m depth. Over 75 % of the carbon is retained over 500 years. Most of the leakage to that atmosphere occurs in the Southern Ocean and in the North Atlantic, where the cold dense waters of the deep ocean contact the atmosphere. (Simulations were performed at LLNL for DOCS under OCMIP protocols.)

The effectiveness of CO<sub>2</sub> disposal is affected by both transport and chemical considerations. Wong and Mattear [1993] find that the effectiveness of CO<sub>2</sub> injection off the coast of Japan would be somewhat limited by the low carbonate-ion concentrations of North Pacific waters. In other basins, interactions between injected CO<sub>2</sub> and carbonate sediments could significantly increase the effectiveness of deep-sea CO<sub>2</sub>

injection [De Baar, 1992; Wilson, 1992; Cole *et al.*, 1993].

There are trade-offs between maximizing effectiveness and minimizing biological impacts of direct injection. Isopycnal (nearly horizontal) dispersion is many millions of times more efficient than diapycnal (nearly vertical) dispersion; thus, enhancing vertical dispersion is critical to minimizing pH impacts both in the near field and in the far field. Thorkildsen and Alendal [1997] modeled the near-field dynamics of a 1-cm-diameter CO<sub>2</sub> droplet in sea-water at 1 km depth. In this range the CO<sub>2</sub> is less dense than the surrounding seawater, and they found that the buoyant rise of the liquid CO<sub>2</sub>, followed by the sinking of the CO<sub>2</sub>-laden seawater led to the dispersal of the CO<sub>2</sub> over a vertical range of 250 m. Morishita *et al.* [1993] found that the results of such calculations are sensitive to the rate of CO<sub>2</sub> dissolution, which in turn depends on droplet size. Droplet size can be manipulated [Teng *et al.*, 1997] to optimize the trade-off between increased dispersion of the CO<sub>2</sub> near the plume source and decreased mean depth, and hence effectiveness, of CO<sub>2</sub> injection. Hirai *et al.* [1997] found that the formation of clathrates on the CO<sub>2</sub> droplet surface impeded dissolution of the released CO<sub>2</sub>, which could increase dispersion of released CO<sub>2</sub>. Brewer *et al.* [1999, 2000] have been conducting *in situ* experiments with submersibles to provide the basic data on which CO<sub>2</sub> droplet dissolution models can be based.

It has been suggested that the effectiveness of deep-sea disposal would be increased if the CO<sub>2</sub> formed clathrates and/or a clathrate-covered CO<sub>2</sub> lake on the seafloor [e.g., Nakashiki, 1997; Spencer and North, 1997]. Ohsumi *et al.*

[1992] have modeled the behavior of a CO<sub>2</sub> lake on the sea floor, based on a set of laboratory experiments of CO<sub>2</sub> properties under relevant conditions. They found that it was important to take into consideration the increase in density of the overlying seawater and assumed that the rate of dissolution of the "lake" would be controlled by transport of carbon in the overlying boundary layer. Observations reported by Nakashiki [1997] also indicate that bottom boundary layer processes would control dissolution of a CO<sub>2</sub> lake.

### Estimating the effectiveness of direct injection

In this next section, we estimate the effectiveness of ocean sequestration as a function of depth of injection. We performed a set of simulations of direct injection of CO<sub>2</sub> into the ocean using both a one dimensional box-diffusion model [Caldeira *et al.*, 1998] and in a three dimensional global general circulation model [Caldeira and Duffy, 2000].

#### One dimensional ocean model.

For the one dimensional model, we represented the ocean by a box-diffusion model [Oeschger *et al.*, 1975; Siegenthaler, 1983] with a 75 m thick mixed-layer and a total depth of 3800 m, as described by Caldeira *et al.* [1998]. Ocean carbon chemistry [Stumm and Morgan, 1981] is calculated using a surface temperature of 18 °C, salinity of 35 psu, and alkalinity of 2.23 eq m<sup>-3</sup>, with constants as specified in Roy *et al.* [1993], Dickson [1990], Millero [1995], and Weiss [1974]. The eddy diffusion and gas-transfer velocity coefficients were chosen such that the change in ocean <sup>14</sup>CO<sub>2</sub> inventory between 1945 and

1975 matches the estimated 1975 bomb radiocarbon inventory [Broecker *et al.*, 1995] of  $305 \times 10^{26}$  atoms, and the modeled 1975 ocean mean and surface ocean  $\Delta^{14}\text{CO}_2$  matches the basin-volume-weighted mean of the natural plus bomb  $\Delta^{14}\text{CO}_2$  values measured in the GEOSECS program [Broecker *et al.*, 1985]. This tuning yielded a vertical eddy diffusion coefficient is  $8,820 \text{ m}^2 \text{ yr}^{-1}$  at the base of the mixed-layer, diminishing with an e-folding length scale of 500 m to a minimum of  $2,910 \text{ m}^2 \text{ yr}^{-1}$  at the ocean bottom. The tuned gas transfer velocity is equivalent to  $0.0543 \text{ mol m}^{-2} \mu\text{atm}^{-1} \text{ yr}^{-1}$  at  $18^\circ\text{C}$ . In this model, the state variables are  $^{12}\text{C}$ ,  $^{13}\text{C}$ , and  $^{14}\text{C}$  masses or concentrations, not ratios or normalized ratios such as  $\Delta^{14}\text{C}$  or  $\delta^{13}\text{C}$ . Throughout, fractionation factors for  $^{14}\text{C}$  are assumed to be the square of the  $^{13}\text{C}$  fractionation factor, and all fractionation factors are from Tans *et al.* [1993]. Because  $^{13}\text{C}$  and  $^{14}\text{C}$  compose a very small fraction of the total C atoms, we use  $^{12}\text{C}$  mass and fluxes interchangeable with C mass and fluxes.

#### Three dimensional ocean model.

For the three dimensional simulations, we used the same configuration of the LLNL ocean general circulation model as described in more detail in Caldeira and Duffy [2000]. The LLNL ocean general circulation model is based on the GFDL Modular Ocean Model (MOM) [Pacanowski *et al.*, 1991], with the addition of the Gent-McWilliams parameterization [Gent and McWilliams, 1990] of transport of tracers by subgrid scale eddies and coupling to the dynamic/thermodynamic sea ice model of Oberhuber [1993]. Our model uses a mesh of 2 degrees (latitude) by 4 degrees (longitude) with 23 vertical levels. The

model was tuned to approximately simulate the  $\Delta^{14}\text{C}$  values observed in the deep central North Pacific ocean. The model results shown here represent the model configuration that is LLNL's entry in the Ocean Carbon-cycle Model Intercomparison Project (OCMIP; <http://www.ipsl.jussieu.fr/OCMIP>).

#### Model simulations

Both the one and three dimensional models were run under the sequestration scenarios described in the OCMIP sequestration protocols described at <http://www.ipsl.jussieu.fr/OCMIP>. The atmospheric  $\text{CO}_2$  concentration was specified to be the IPCC S650 scenario, and injection was performed at 7 different locations at 3 different depths at a rate of  $0.1 \text{ PgC/yr}$  for 100 years starting in year 2000 and continuing another 400 years with no injection. This S650 protocol is conservative in that injected  $\text{CO}_2$  that leaks out to the atmosphere is not permitted to re-enter the ocean, as it would in the real world (see discussion below). Injection locations are near: (1) the Bay of Biscay, (2) New York City, (3) Rio de Janeiro, (4) San Francisco, (5) Tokyo, (6) Jakarta, and (7) Bombay.

#### Model results

The basic results for the model simulations are presented in Table 1 and Figure 2. The figure represents the amount of the injected carbon remaining in the ocean as a function of time for all of the injection locations, as well as for the one dimensional model. With perfect retention the lines would slope up at  $0.1 \text{ PgC yr}^{-1}$  until year 100 and then remain at  $10 \text{ PgC}$  thereafter. Injection at 3000 m is quite effective at sequestering carbon from the atmosphere for several

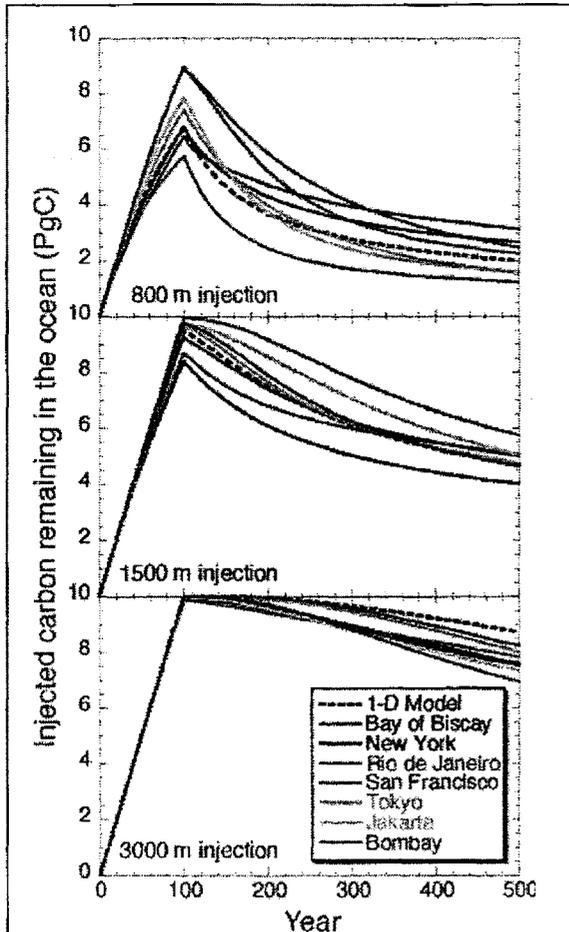


Figure 2. Comparison of one-dimensional and three-dimensional model results for injections as described under OCMIP protocols. The top, middle, and bottom panels show results for injections at 800 m, 1500 m, and 3000 m depth, respectively. For exploring basic conceptual issues, a one-dimensional model adequately represents the behavior of the three-dimensional model.

centuries, whereas injection at shallower depths is less effective. In general, injections into the Pacific Ocean are more effective than injection at the same depth in the Atlantic Ocean.

The one dimensional box-diffusion model represents the behavior of the three dimensional model quite well at 800 m and 1500 m, but the model somewhat overpredicts retention at the

Table 1. CO<sub>2</sub> retention at 500 years.

	Box-diffusion model	Ocean GCM
Depth of injection	500-year retention	Mean 500 year retention $\pm 1$ S.D.
800 m	20 %	21 $\pm$ 7 %
1500 m	46 %	49 $\pm$ 5 %
3000 m	87 %	76 $\pm$ 4 %

Table 1. CO<sub>2</sub> remaining at 500 years. Comparison of retention of CO<sub>2</sub> injected into the ocean at three different depths using a one-dimensional box-diffusion model and a three-dimensional ocean GCM. Especially at shallower depths, the 1-D model results accord well with 3-D model results, indicating that the 1-D model is an appropriate tool for exploring basic conceptual issues associated with direct CO<sub>2</sub> injection into the ocean.

3000 km depth. This difference at depth is due to the fact that the one dimensional model lacks an advective pathway to more rapidly bring carbon from the deep ocean to the ocean surface.

Deeper injection is associated with increased retention in both models. In the 3-D model, the standard deviation of the retention across the seven injection locations is small compared to the difference in mean retention across the three injection depths. This suggests that depth of injection is the major control on retention efficiency for injected carbon dioxide.

We conclude that for studies of fundamental issues in direct ocean CO<sub>2</sub> injection, a one dimensional model provides a reasonable prediction. Of course, comparison of different potential sites or an examination of biotic impacts

would require site-specific three dimensional modeling.

### **Accounting for a leaky ocean**

Occasionally, we hear claims that > 80 % of the carbon injected in the ocean will remain in the ocean. Then, in other contexts we hear that all the CO<sub>2</sub> leaks out on a time scale of 300 years for some injection locations. How can these superficially differing claims be reconciled?

#### **A leaky geologic reservoir**

To clear up confusion, we will discuss leakage of CO<sub>2</sub> from a geologic reservoir and then draw parallels between this discussion and leakage of CO<sub>2</sub> from the ocean.

If CO<sub>2</sub> were injected into a leaky geologic reservoir, this would be equivalent to a slow flux of CO<sub>2</sub> to the atmosphere over an extended period of time. If a system of carbon-trading credits were in place, one of several reasonable approaches to account for this CO<sub>2</sub> flux would be to charge for the CO<sub>2</sub> as it enters the atmosphere. Some of this leaking CO<sub>2</sub> will enter the ocean through the natural processes by which the ocean takes up anthropogenic CO<sub>2</sub>. If we were to ask the question, how much carbon is sequestered at a given time by CO<sub>2</sub> injection to the leaky reservoir, the answer would be: the amount of CO<sub>2</sub> remaining in the geologic reservoir. We would not add on to this the amount of carbon that has fluxed through the atmosphere to the ocean.

#### **A leaky oceanic reservoir**

The situation with ocean carbon sequestration is less clear because CO<sub>2</sub> degasses from the ocean to the

atmosphere and is reabsorbed by the ocean. How should this be accounted for?

In judging the effectiveness of the leaky geologic sequestration case, we did not consider the flux that would have been driven into the ocean by CO<sub>2</sub> leaked to the atmosphere. Similarly, when judging the effectiveness of ocean carbon sequestration, we should not consider the reabsorption of CO<sub>2</sub> that has degassed to the atmosphere.

This can be accomplished by considering the atmospheric boundary conditions under which a computer model could be run to estimate sequestration effectiveness for a given amount of CO<sub>2</sub> deposited in the ocean at some discrete time. The model could be run with a prescribed atmospheric CO<sub>2</sub> concentration, or it could be run with an atmospheric CO<sub>2</sub> concentration that increases as the sequestered CO<sub>2</sub> outgasses.

Under the fixed-atmospheric CO<sub>2</sub> boundary condition, all of the injected CO<sub>2</sub> will have leaked back to the atmosphere in the steady state. Under the responsive atmospheric CO<sub>2</sub> boundary condition, around 80 % of the injected CO<sub>2</sub> remains in the ocean in the steady state.

We suggest that the fixed atmospheric CO<sub>2</sub> boundary condition is the appropriate one for measuring the effectiveness of ocean sequestration strategies. With this boundary condition, we do not take credit for the natural uptake of excess CO<sub>2</sub> from the atmosphere.

To illustrate some of these issues we present some results from the one dimensional box-diffusion model described above. Figure 3 shows the

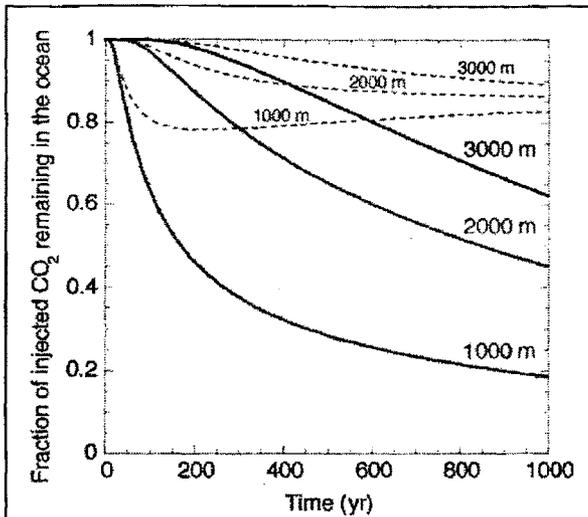


Figure 3. Fraction of injected  $\text{CO}_2$  remaining in the ocean at three different depths as predicted by the one-dimensional model described in the text. Solid lines represent the fixed atmospheric  $\text{CO}_2$  boundary condition. Dashed lines represent the responsive atmospheric  $\text{CO}_2$  boundary condition. The solid lines represent the appropriate amount of carbon to attribute to purposeful carbon sequestration.

results of the model for amount of carbon remaining in the ocean as a function of time, for the cases in which atmospheric  $\text{CO}_2$  content both does and does not respond to leakage from the ocean, from a base state of 280 ppm. Figure 4 shows the corresponding fluxes of  $\text{CO}_2$  to the atmosphere.

#### Analytic framework with a worked example

How do we compare the benefits of storing  $\text{CO}_2$  in a leaky reservoir with, say, atmospheric release or permanent sequestration? Here, we develop a mathematical formalism to permit such comparison. Our formalism is based on the concepts of

*global warming cost, GWC*, the net present value of the costs associated

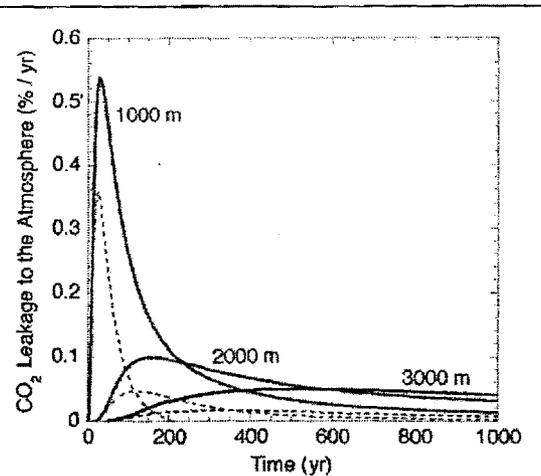


Figure 4. Fluxes of carbon to the atmosphere for the injection scenarios represented in Fig. 3. A 0.1 on the vertical axis means that 0.1 % of the initially injected  $\text{CO}_2$  leaks back to the atmosphere during a given year. Notice that leakage of injected carbon to the atmosphere starts off at zero, and then increases to some maximum before diminishing towards zero. Ocean sequestration moves carbon emissions from the present to the future, potentially to economic benefit, due to the role of discounting in reducing the present value of costs incurred in the distant future.

with a time-history of emissions of greenhouse gases, and

*sequestration potential, SP*, the fraction of global warming costs avoided by sequestering carbon in a reservoir, relative to the cost of immediate atmospheric release.

Let us suppose that the cost of carbon released to the atmosphere is  $C(t)$ , where this cost may vary as a function of time,  $t$ . Depending on the application,  $C(t)$  may represent  $\text{CO}_2$  taxes, cost of  $\text{CO}_2$  credits, direct and indirect environmental costs, or other relevant measures associated with release of  $\text{CO}_2$  to the atmosphere.

Net present value is a convenient tool for evaluating carbon sequestration options [Reilly, 2001]. Let us suppose the

reservoir leaks at a rate,  $L(t)$ . Then, the global warming cost,  $GWC$ , for a real discount rate of  $i$ , would be the net present value of the cost of emissions from the leaky reservoir:

$$GWC = \int_{t=0}^{\infty} \frac{C(t)L(t)}{(1+i)^t} dt . \quad (1)$$

Let us suppose a reservoir leaks at a rate proportional to the amount of  $\text{CO}_2$  remaining in the reservoir. If the residence time of  $\text{CO}_2$  in the reservoir is some time,  $\tau$ , then for an initial storage of  $M$  moles of carbon the leakage can be described by

$$L(t) = \left( \frac{M}{\tau} \right) e^{-t/\tau} . \quad (2)$$

We note that equation (2) is not an accurate representation of leakage from the ocean, but is used here as a simple example. Equation (2) starts off with a maximum leakage immediately after a  $\text{CO}_2$  injection, whereas oceanic injection starts off with near-zero leakage, with the leakage increasing to some maximum and then diminishing (Figure 4).

If, for simplicity, we assume the cost,  $C(t)$ , remains constant with time at some value,  $C_0$ , then substituting equation (2) into equation (1) and integrating, we have that the global warming cost of emissions from an idealized leaky reservoir would be

$$GWC = \frac{M \cdot C_0}{1 + \tau \cdot \ln[1 + i]} . \quad (3)$$

The global warming cost for permanent sequestration ( $\tau = \infty$ ) is zero. The global warming cost of immediate emission to the atmosphere ( $\tau = 0$ ) would be the mass of the emission,  $M$ , times the cost of emission per unit mass,  $C_0$ .

Table 2. Symbols used in the text

Variable	Units	Description
$t$	yr	Time after $\text{CO}_2$ is injected into the reservoir
$\tau$	$\text{yr}^{-1}$	Residence time of $\text{CO}_2$ in the sequestration reservoir
$M$	Mol C	Molar mass of carbon
$L(t)$	Mol C $\text{yr}^{-1}$	Rate of $\text{CO}_2$ leakage from the reservoir
$C(t)$	$\$ (\text{Mol C})^{-1}$	Cost per mol C released to the atmosphere
$i$	$\text{yr}^{-1}$	Real economic discount rate
$SP$	—	Fraction of global warming costs, $GWC$ , avoided, due to sequestration in a reservoir
$GWC$	$\$$	Present-value of the cost associated with a time series of $\text{CO}_2$ emissions
$GWC_0$	$\$$	The cost associated with a $\text{CO}_2$ emission

$$GWC_e = M \cdot C_0 \quad (4)$$

We define the sequestration potential to be the avoided discounted global warming cost achieved by sequestering CO<sub>2</sub> in a reservoir, divided by the discounted global warming cost of atmospheric emission of that CO<sub>2</sub>.

$$SP = \frac{GWC_e - GWC}{GWC_e} \quad (5)$$

The sequestration potential, *SP*, takes on the value of one for permanent sequestration, and zero for immediate atmospheric release.

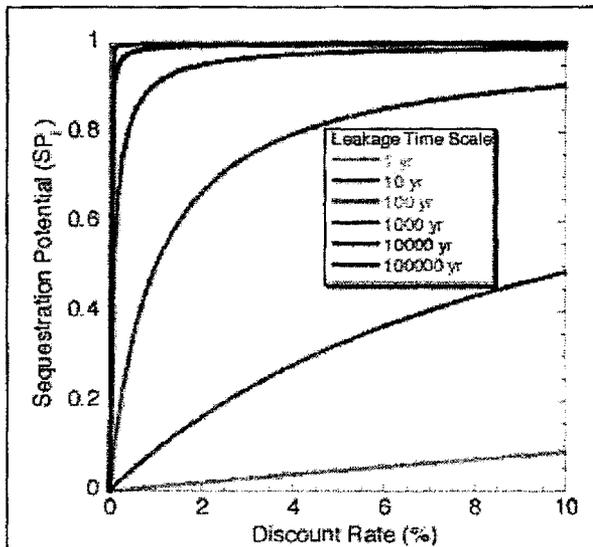


Figure 5. Sequestration potential for an idealized leaky reservoir as a function of discount rate for a variety of residence times ( $\tau$ ). For a discount rate of 5 % per year, sequestering CO<sub>2</sub> in a reservoir that leaks on the time scale of 100 yr saves approximately 80 % of the global warming cost of the CO<sub>2</sub>. For this discount rate, a reservoir that leaked on the 1000 yr time scale would save ~98 % of the global warming cost. Curves are calculated from equation (6).

In our simplified example (i.e., constant CO<sub>2</sub> emissions cost, reservoir leaks with a single exponential time scale) the sequestration potential, *SP*, can be found analytically as a function of the residence time of carbon in the reservoir,  $\tau$ , and the real discount rate, *i*, by substituting equations (3) and (4) into equation (5):

$$SP = \frac{\tau \cdot \ln[1 + i]}{1 + \tau \cdot \ln[1 + i]} \quad (6)$$

Results for the sequestration potential as a function of time scale,  $\tau$ , and discount rate, *i*, are presented in Figures 5 and 6.

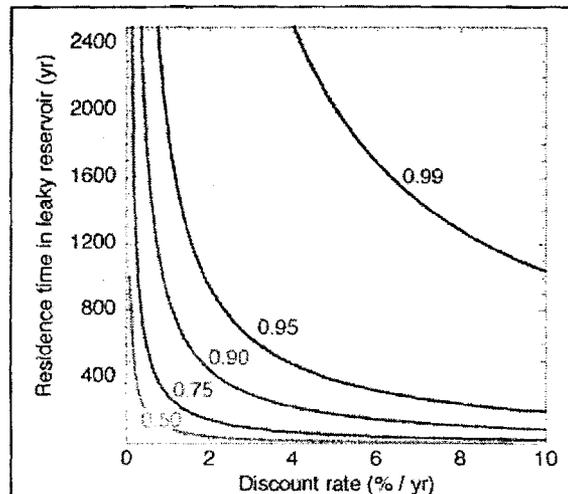


Figure 6. Sequestration potential for an idealized leaky reservoir as a function of discount rate and residence time. Residence time is related to the concept of a half-life of CO<sub>2</sub> in the leaky reservoir. (Half-life = 0.693 x residence time) For a discount rate of 5 % per year, sequestering CO<sub>2</sub> in a reservoir that leaks on the time scale of 100 yr saves approximately 80 % of the global warming cost of the CO<sub>2</sub>. For this discount rate, a reservoir that leaked on the 1000 yr time scale would save ~98 % of the global warming cost. Curves are calculated from equation (6).

Using results from the 1-D model

Ocean models do not, in general, allow analytic representations of their results. Nevertheless, equations (1) and (5) can be numerically integrated using fluxes predicted by the models. An example of these fluxes is represented in Figure 4. (These fluxes correspond to the carbon storage shown in Figure 3.) We used the box-diffusion model to calculate sequestration potential as a function of injection depth and discount rate. These results are plotted graphically in Figure 7.

Under the assumption of a constant cost of carbon emission and a 4 % discount rate, injecting only 900 m deep avoids ~90 % of the associated global warming costs; an injection 1700 m deep avoids > 99 % of the associated global warming costs. At a 6 % discount rate, an 750 m injection avoids > 90 % of the costs, whereas a 1400 m injection would avoid > 99 % of the costs.

## Conclusions and Discussion

We have performed simulations of ocean carbon sequestration using one- and three dimensional ocean carbon cycle models. We find that the one dimensional model results accord quite well with the three dimensional model results. Therefore, the one dimensional model is a tool of choice for exploring basic issues in direct oceanic CO<sub>2</sub> injection that do not depend on site-specific or local characteristics of the injection. (For example, the 1-D model would not be appropriate for near field biotic impact studies.) Both one and three dimensional model results suggest that > 75 % of carbon injected at 3000 m depth is sequestered in the oceans for > 500 years.

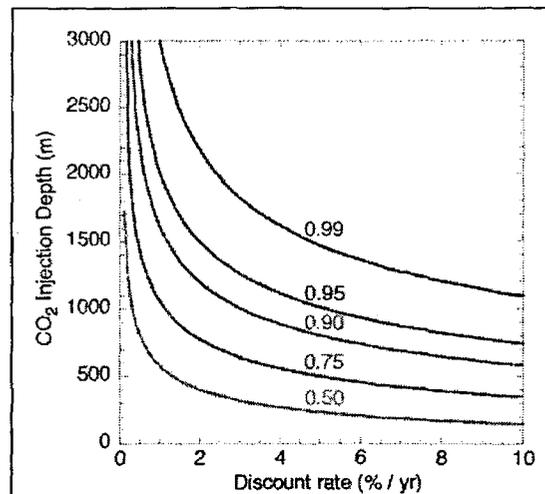


Figure 7. Sequestration potential for direct CO<sub>2</sub> injection as a function of discount rate and CO<sub>2</sub> injection depth, as calculated by the one-dimensional box-diffusion model. A 2000 m injection at a 3 % discount rate would avoid over 99 % of associated global warming cost, assuming constant carbon emission cost.

When CO<sub>2</sub> is sequestered in the oceans via direct injection, some of the CO<sub>2</sub> leaks out to the atmosphere and is then reabsorbed by the oceans. Our analysis of the problems suggests that this reabsorption should be considered part of the natural oceanic uptake of anthropogenic CO<sub>2</sub> and should not be credited towards ocean carbon sequestration.

We have defined measures of global warming cost, *GWC*, and the percentage of global warming cost avoided by sequestration, denoted sequestration potential, *SP*, and applied these measures to an idealized leaky carbon sequestration reservoir and the oceans.

Our analysis suggests that CO<sub>2</sub> injections into mid-depth waters may be an effective sequestration strategy, and injection into the deepest waters may not be economically justifiable. This conclusion could change if carbon emission costs were to rise rapidly in the

future. We find that ~98 % of global warming costs, *GWC*, can be avoided by CO<sub>2</sub> injection at ~1400 m with a 4 % discount rate, if the costs of carbon emission are taken to be constant in time. Under these same assumptions, it would take injection at ~1600 m to avoid ~99 % of the cost. The question of whether it makes sense to inject ~200 m deeper to avoid an additional 1 % of the global warming cost is largely an economic one. A fuller economic analysis would, of course, need to bring into consideration direct and indirect costs associated with implementing carbon sequestration strategies, and consider feedbacks between economic choices and carbon emission prices.

It may turn out that rational economic analysis counsels against deep injections that are retained in the oceans for a long time in favor of mid-depth injections that achieve a relatively high sequestration potential. The effectiveness of ocean carbon sequestration is more site-dependent for injections at shallow depths than it is for deep injection (Figure 2). Therefore, for relatively shallow injection depths, site evaluation will depend to a greater degree on understanding local site characteristics.

The issue of the appropriate discount rate to use in problems involving intergenerational transfer of environmental assets is difficult. Arguments can be made that the appropriate discount rate for such situations should be near zero. At a zero discount rate with constant cost for carbon emission, there is no advantage to ocean carbon sequestration. Nevertheless, environmental costs can change with time, and it may prove useful to push carbon emissions to the distant future to slow near-term rates of climate change. In this

case, ocean carbon sequestration could prove useful even at zero discount rate. Nevertheless, with constant carbon emissions costs, even modest discount rates (e.g., 3 %) allow mid-depth oceanic injections of CO<sub>2</sub> to avoid the vast majority of global warming costs (Figure 7).

Most the carbon we emit into the atmosphere will end up residing in the ocean eventually. Ocean sequestration places the carbon there immediately, thus bypassing the atmosphere where CO<sub>2</sub> may have adverse impacts on climate as well as on the biota living in the ocean surface.

However, ocean carbon sequestration will only be acceptable if it can be shown that it is environmentally and economically preferable to alternative courses of action. Ocean sequestration is not the entire answer to the energy/climate/carbon problem, but it may be part of the answer, especially for coastally located CO<sub>2</sub> point sources far from acceptable geologic reservoirs.

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