Differing methods of accounting ocean carbon sequestration efficiency

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[1] Presently, much of CO_2 fossil-fuel emissions are removed from the atmosphere through natural ocean uptake of CO_2. Many schemes have now been proposed by which the accumulation of anthropogenic CO_2 in the atmosphere could be slowed with intentional further storage of CO_2 in the ocean. Our review of the literature indicates inconsistency in whether ambient ocean carbon uptake is included when accounting for the effectiveness of such schemes. This inconsistency is a consequence of differing choices of atmospheric boundary condition. In the case of one particular form of ocean sequestration, namely direct injection of liquefied CO_2 emissions into the ocean interior, this choice is the determination of whether the atmospheric CO_2 concentration responsively increases due to leakage of injected carbon from the ocean or retains a specified value. We first show how results of simulations using these two different boundary conditions can be related with the convolution of an atmosphere pulse release. We then use a numerical model to present a more complete analysis of the role of these boundary conditions. Finally, we suggest that a responsive atmospheric CO_2 boundary condition is appropriate for predicting future carbon concentrations, but a specified atmospheric CO_2 boundary condition is appropriate for evaluating how much CO_2 storage should be attributed to an ocean storage project. *INDEX TERMS:* 4806 Oceanography: Biological and Chemical: Carbon cycling; 4203 Oceanography: General: Analytical modeling; 4263 Oceanography: General: Ocean prediction; 4271 Oceanography: General: Physical and chemical properties of seawater; *KEYWORDS:* carbon cycle, ocean sequestration, ISAM

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1. Introduction

[2] Continued accumulation of carbon dioxide in the atmosphere may cause an increase in climate change [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Therefore it is important to explore viable solutions to the problem of transforming our present energy usage patterns so that less environmental risk in incurred [*Hoffert et al.*, 1998; *Caldeira et al.*, 2002]. One such option may be the sequestration into the ocean of carbon emissions stemming from fossil fuel usage. Ocean carbon sequestration might play a role in a broader portfolio of options, including strategies to reduce CO_2 emission through lessened fossil-fuel dependence and greater efficiency.

[3] Because the ocean ultimately absorbs most of the CO_2 emitted to the atmosphere, strategies that seek to sequester even greater quantities of CO_2 within the ocean can be viewed as attempts to accelerate ocean uptake and storage of anthropogenic CO_2. Some schemes aim to accelerate the downward flux of carbon into the ocean by stimulating the natural "biological pump," thereby causing an ocean surface depletion of carbon that results in the absorption of more CO_2 from the atmosphere. This can be achieved through the addition to the ocean surface of micronutrients such as iron and/or macronutrients such as phosphate and nitrate [e.g., *Sarmiento and Orr*, 1991]. Other schemes aim to deliver CO_2 to the deep ocean by direct injection, thus bypassing the slow mixing processes that ultimately transfer excess atmospheric CO_2 from the atmosphere to the deep ocean [e.g., *Marchetti*, 1977]. Still other schemes seek to increase the alkalinity of the ocean, which would act to permanently remove carbon dioxide from the atmosphere [*Jones and Young*, 1998].

[4] Portions of carbon sequestered in the deep ocean can eventually escape into the atmosphere over time through ocean circulation to the surface and air-sea exchange at the surface. Therefore, careful evaluation of the portion of sequestered carbon remaining in the ocean over time,

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the efficiency, is crucial. The efficiency of ocean carbon sequestration is determined by the physical, chemical, and biological processes that control the exchange of carbon between atmosphere and ocean, including ocean circulation, marine biology, and atmospheric CO_2 concentration. At present, modeling studies have investigated the sensitivity of the efficiency of different ocean carbon sequestration schemes to a number of factors, such as the location and depths of injection for direct injection sequestration [e.g., *Hoffert et al.*, 1979; *Kheshgi et al.*, 1994; *Orr et al.*, 2001a], the representation of marine biological productivity and remineralization [e.g., *Sarmiento and Orr*, 1991; *Kurz and Maier-Reimer*, 1993; *Gnanadesikan et al.*, 2003] and different background CO_2 concentrations [e.g., *Kheshgi and Archer*, 2004].

[5] Two approaches to the modeling of carbon sequestration effectiveness have been used, differentiated from each other by the choice of atmospheric boundary condition. In the first approach, atmospheric CO_2 concentrations are prescribed and are not affected by air-sea carbon flux [e.g., *Orr et al.*, 2001a; *Caldeira et al.*, 2002; *Wickett et al.*, 2003; *Herzog et al.*, 2003], hereinafter identified as the prescribed concentration approach. In the second approach, CO_2 emissions are prescribed and the resultant CO_2 concentration is determined from both the emissions and the calculated cumulative air-sea carbon flux [e.g., *Kurz and Maier-Reimer*, 1993; *Kheshgi and Archer*, 2004; *Gnanadesikan et al.*, 2003], hereinafter identified as the prescribed emission approach. These two approaches have been used without a pointed discussion of their significance. Owing to this, results provided by different studies are difficult to compare, thereby complicating analysis by policy makers. For example, in a paper evaluating carbon costing, *Shoji and Jones* [2001] note a lack of accounting for pertinent fertilization research due to the use of different boundary conditions between studies. The issue of distinguishing between natural and induced carbon sequestration is broadly relevant. However, the influence of these atmospheric boundary conditions is most clear and most pronounced in the case of direct injection, so this scheme and a generic hypothetical scheme are given focus hereinafter.

[6] To define each choice of atmospheric boundary condition in the context of atmospheric CO_2 mitigation strategies, we present ocean direct injection in a broader context through comparison with storage of CO_2 into a hypothetical reservoir that leaks at a rate proportional to the amount of stored CO_2 currently remaining. Both this reservoir and ocean injection sequestration may be described as movement of carbon emissions into a leaky reservoir other than the atmosphere. For both techniques, CO_2 leakage into the atmosphere will be offset by oceanic absorption or re-absorption that will depend on the atmospheric CO_2 boundary conditions adopted. The purpose of this paper is to describe the roles of these conditions on the predicted efficiency of ocean carbon storage. First, we show how results obtained under these two boundary conditions are mathematically related. Then, using a simple ocean carbon cycle model, we demonstrate how adopted boundary conditions influence the estimated sequestration effectiveness for both carbon delivery into a hypothetical leaky reservoir and direct ocean injection over a range of different atmospheric CO_2 background conditions.

2. Mathematical Expression of Boundary Condition Relationship

[7] To illustrate the basic conceptual issues associated with the choice of boundary conditions in ocean sequestration simulations, we present a simple linear representation of (1) a hypothetical leaky reservoir, (2) oceanic uptake of atmospheric carbon dioxide, and (3) leakage of CO_2 injected into the deep ocean. The explicit assumption of linearity in the time-varying ocean uptake of atmospheric emission has been used as a tool in past research [*Wigley et al.*, 1991; *Harvey*, 1989; *Maier-Reimer and Hasselmann*, 1987]. In addition, *Joos et al.* [1996] and *Kheshgi and Archer* [2004] have described a new analytical approach that takes into account key nonlinearities (e.g., the dependence of CO_2 solubility on present CO_2 concentrations) in the ocean behavior to estimate modeled ocean response with far greater accuracy. Here we present a linear system to show the basic mathematical relationships between results obtained under different boundary conditions; below, we present results using a numerical model that considers nonlinearities introduced by carbonate chemistry.

[8] The effect of boundary conditions on carbon storage is best illustrated by first considering the case of a hypothetical leaky reservoir. Let $A(t)$ represent the amount of carbon remaining in the atmosphere relative to the amount placed in the atmosphere at time t_0. Assuming that the ocean is the only sink for this carbon, then ocean uptake of atmospheric carbon is $-\frac{dA}{dt}$. Let $R(t)$ represent the amount of carbon remaining in a hypothetical leaky reservoir relative to the amount placed in the reservoir at time t_0. Leakage to the atmosphere is then $-\frac{dR}{dt}$. The fractional amount of carbon in the ocean at time t_1 resulting from the placement of CO_2 into a leaky reservoir at time t_0, $M_R(t_1)$, is then given by

$$M_R(t_1) = \int_{t_0}^{t_1} \left[\frac{dR}{dt}\right]_{t=\tau} \times \left[\frac{dA}{dt}\right]_{t=t_1-\tau} d\tau. \quad (1)$$

At time t_1, M_R, the fraction of CO_2 in the atmosphere from the leaky geologic reservoir, would be

$$A_R(t_1) = 1 - [R(t_1) + M_R(t_1)], \quad (2)$$

where $R(t_1) + M_R(t_1)$ represents the fractional amount of carbon remaining in the geologic reservoir plus that which has been absorbed by the ocean.

[9] Ocean storage computed under two different boundary conditions follows a similar line as above. Let $S(t)$ represent the amount of additional carbon remaining in the sea relative to some initial amount placed in the sea at time t_0, as calculated under constant atmospheric CO_2 boundary conditions; then, leakage to the atmosphere is $-\frac{dS}{dt}$. Analogous to equation (1), $M_S(t_0)$, the amount of carbon leaked to the atmosphere from the ocean injection that was then subsequently re-absorbed by the ocean from the atmosphere, is given by

$$M_S(t_1) = \int_{t_0}^{t_1} \left[\frac{dS}{dt}\right]_{t=\tau} \times \left[\frac{dA}{dt}\right]_{t=t_1-\tau} d\tau. \quad (3)$$

At time t_1, A_S, the fraction of CO_2 in the atmosphere from the ocean injection, would be

$$A_S(t_1) = 1 - [S(t_1) + M_S(t_1)], \quad (4)$$

where $[S(t_1) + M_S(t_1)]$ represents the fractional amount of carbon remaining in the ocean that has never degassed to the atmosphere plus carbon which has degassed to the atmosphere and been subsequently re-absorbed by the ocean.

[10] For carbon accounting purposes, the amount of sequestration attributed to deliberate sequestration into the hypothetical leaky reservoir should be $R(t_1)$, the amount remaining in the reservoir, and should not be the reduction in atmospheric CO_2 content which includes the natural oceanic uptake of leaked CO_2, $M_R(t_1)$. The case of ocean CO_2 direct injection is analogous. The amount of carbon that should be attributed to storage in the ocean is $S(t_1)$, the determination of the prescribed concentration approach which excludes the fraction of carbon that has leaked to the atmosphere and been subsequently re-absorbed by the oceans, $M_S(t_1)$. The determination of the prescribed emission approach, $[S(t_1) + M_S(t_1)]$, on the other hand, represents the amount of injected carbon that is in the ocean at time t_1. This distinction has large consequences for estimated effectiveness of ocean storage. $S(t_1)$ asymptotes to zero as t_1 gets large, while $M_S(t_1)$ approaches some number, typically in the range of 0.6 to 0.85 (depending on equilibrium atmosphere CO_2, surface ocean temperature, and other factors as determined by our experiments), over several thousands of years. By neglecting to point out the significance of atmospheric boundary conditions, presentations of ocean carbon storage often do not clearly make the distinction between these two cases, a distinction determined entirely by the treatment of oceanic re-absorption of leaking injected CO_2.

[11] The discussion above does not consider nonlinearity introduced by carbonate chemistry. In the following sections, this analysis is expanded using a numerical model that takes into account this nonlinearity. This nonlinearity does not affect fundamental conclusions regarding the application of boundary conditions in problems relating to ocean carbon sequestration.

3. Model Description

[12] For the purpose of analytic tractability, ocean chemistry was linearized in the preceding section. Here a more complete analysis is performed using a numerical ocean model incorporating nonlinear chemical effects. The first-order conclusions of this discussion depend only on timescales of deep-ocean ventilation and air-sea gas exchange. Thus the ocean component of the one-dimensional version of the Integrated Science Assessment Model (ISAM-1D) [*Jain et al.*, 1995] is used. In this model, the ocean is modeled as a one-dimensional upwelling-diffusion water column capped by a mixed layer, which exchanges carbon with a well-mixed atmosphere. Thermohaline circulation is schematically represented by polar downwelling, with return flow to the surface ocean through upwelling. Carbon composition of this downwelling polar water is determined by polar ingassing, upwelling, and diffusion in an explicitly modeled polar region. This differs from the previous version [*Jain et al.*, 1995] which utilized a simple parameterization, π, to determine polar water composition. Two key parameters in the ocean model, eddy diffusivity k and upwelling velocity w are calibrated to match the simulated ^{14}C and ^{13}C distribution in the ocean with those observed [*Jain et al.*, 1995, 1996]. The air-sea exchange of carbon is calculated from the full set of chemical equations of the carbonate system, which include total carbon, alkalinity, phosphate, borate, and silicate [*Peng et al.*, 1987]. The ocean biology carbon cycle component follows the parameterizations specified by the Ocean Carbon Cycle Model Intercomparison Project (OCMIP) [*Orr et al.*, 1999].

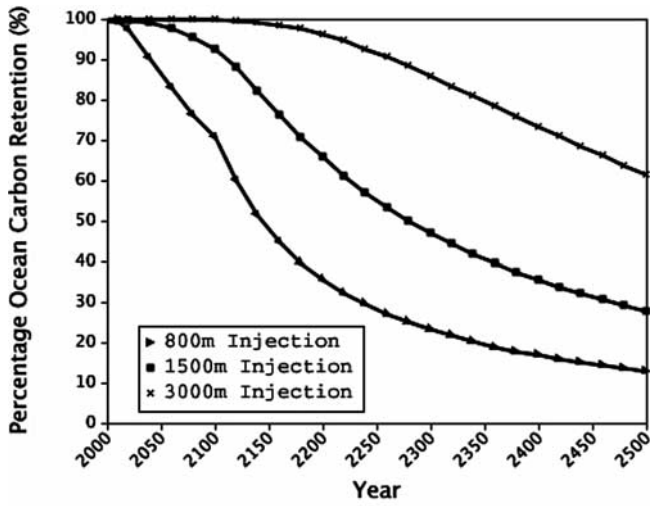

Figure 1. Percentage ocean retention of carbon in response to an OCMIP protocol injection, i.e., continuous injection of 0.1 PgC for 100 years with atmospheric CO_2 prescribed by scenario S650 for injection depths of 800 m, 1500 m, and 3000 m.

[13] The ISAM-1D ocean carbon cycle model is well suited to address the boundary-condition-related issues under study here. The behavior of ISAM closely matches that of globally averaged OGCMS in sequestration experiments (see below). Additionally, the modeled global yearly average uptake of anthropogenic CO_2 during the 1980s is 1.83 PgC per year without reduction of oceanic CO_2 solubility due to increasing sea-surface temperature, and 1.68 PgC per year with this reduction. These results are within the range of OGCM results of 1.5–2.2 PgC [*Orr et al.*, 2001b] as well as *IPCC* [2001] estimates of $1.9 \pm .6$ PgC.

4. OCMIP Benchmark Sequestration Simulations

[14] The standard carbon sequestration experiments described in OCMIP have been used to evaluate ISAM-1D performance in carbon sequestration simulations. Following OCMIP protocols, for each of three depths (800 m, 1500 m, and 3000 m), simulated injections began at year 2000 at a rate of 0.1 PgC/yr for 100 years. Response was then simulated for another 400 years without further injection. Background atmospheric CO_2 concentration was specified by the IPCC S650 scenario. Figure 1 shows the amount of injected carbon remaining in the ocean as a function of time.

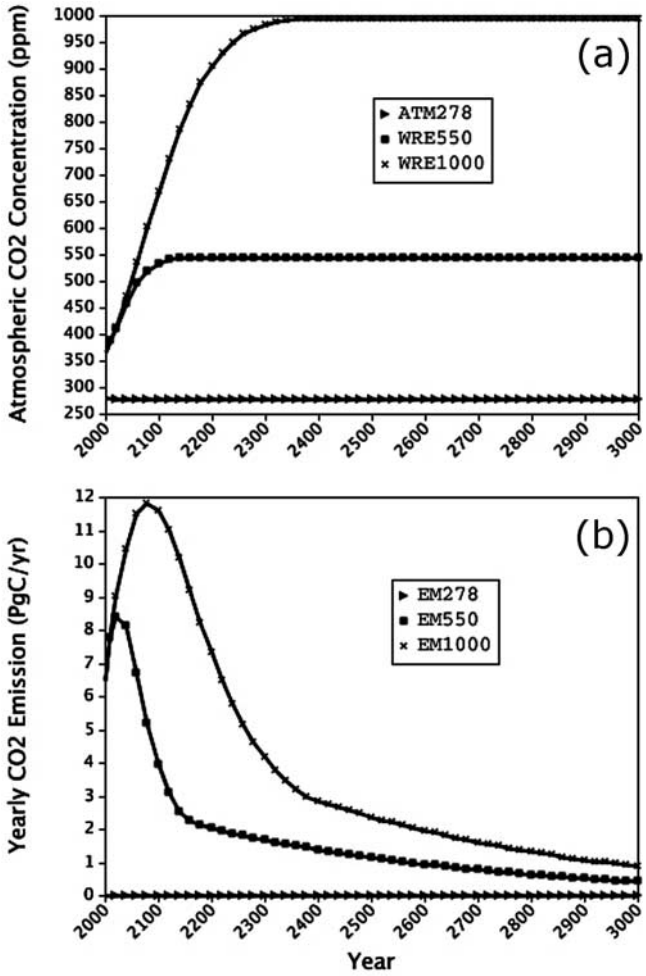

Figure 2. (a) Concentrations of atmospheric CO_2 prescribed by stabilization scenarios WRE550 and WRE1000 in addition to a scenario prescribing constant preindustrial atmospheric CO_2, ATM278. (b) Emission scenarios that would cause levels of atmospheric CO_2 corresponding to these scenarios as determined by the simple ocean carbon cycle model ISAM-1D.

ISAM-1D predicts an storage efficiency of 14%, 29%, and 61% for injections at 800 m, 1500 m, and 3000 m, respectively, in the year 2500, which, are within the ranges (13–39%, 29–59%, and 49–81%, respectively) predicted by seven ocean general circulation models (OGCMs) participating in the OCMIP direct injection simulation intercomparison [*Orr et al.*, 2001a].

5. Influence of Boundary Conditions: Experiment Setup

[15] The two atmospheric boundary conditions for the ocean model are (1) specified atmospheric CO_2 concentration and (2) specified CO_2 emission to the atmosphere. In the former case, air-sea CO_2 fluxes do not affect atmospheric concentrations; in the latter case, they do. These two conditions were tested for various atmospheric CO_2 emission or concentration scenarios. To investigate the effect of these different boundary conditions on the assessment of carbon sequestration effectiveness, ISAM-1D was used to perform, under various CO_2 emission and concentration scenarios, the carbon sequestration experiments for both the case of ocean direct injection and the case of a hypothetical leaky reservoir leaking on an exponential timescale of 400 years for this case (at a rate of 0.25%/yr). In these simulations, three prescribed CO_2 concentration scenarios were used: a constant CO_2 concentration of 278 ppm, representing preindustrial atmosphere (hereinafter referred to as ATM278), and two IPCC CO_2 stabilization scenarios, WRE550 and WRE1000 [*Wigley et al.*, 1996]. In addition, three associated CO_2 emissions scenarios were derived by calculating through inverse modeling the emissions necessary to achieve each of the above three concentration scenarios, hereinafter referred to as EM278, EM550, and EM1000, respectively. Atmospheric CO_2 concentration scenarios and their corresponding emission scenarios used in experiments are shown in Figure 2.

[16] When specifying the WRE stabilization scenarios and their associated emission scenarios, initial conditions for year 2000 were taken from a simulation of the ocean carbon cycle in the historical past. During this simulation, the effects of increasing sea-surface temperature and of CO_2 fertilization of the terrestrial biosphere are included in order to keep model-determined emissions close to historical emissions. Simulations began in the year 2000 and extended for a 1000-year duration. To isolate the effect of the background atmospheric CO_2 conditions for analysis, we assume zero net flux into the terrestrial biosphere and no change in sea-surface temperature. Simulations using EM278 or ATM278 use the steady state of the carbon-cycle system as their initial condition.

[17] We performed simulations of both an impulse addition of 10 PgC to a simple hypothetical leaky reservoir and an impulse injection of 10 PgC at depth 1500 m into the ocean. Ocean retention of injected carbon was determined by the difference in ocean carbon content between the sequestration simulation and a base simulation in which no sequestration occurred.

6. Results and Discussion

[18] For any sequestration scheme, the total CO_2 intended for storage may be divided into three pools over time, (1) the fraction of CO_2 that remains in storage, (2) the fraction of CO_2 that has leaked into the atmosphere and remains there, and (3) the fraction of CO_2 that has leaked into the atmosphere and been absorbed by natural sinks of carbon, most notably the ocean. Figure 3a shows how these three fractions are related to the choice of atmospheric boundary condition for the modeling of a hypothetical reservoir leaking at a rate of 0.25% of stored CO_2 per year (this leakage rate has been chosen to facilitate comparison with ocean direct injection). The prescribed concentration case (modeled simply by analytical solution for the above leakage rate) consists only of pool 1, the fraction of CO_2 that remains in the storage. The prescribed emission case is the sum of pools 1 and 2, and represents the total amount of initial carbon not within the atmosphere. This case was modeled using ISAM-1D by adding the calculated leakage to the prescribed emissions of EM550, and determining yearly air-sea flux (the

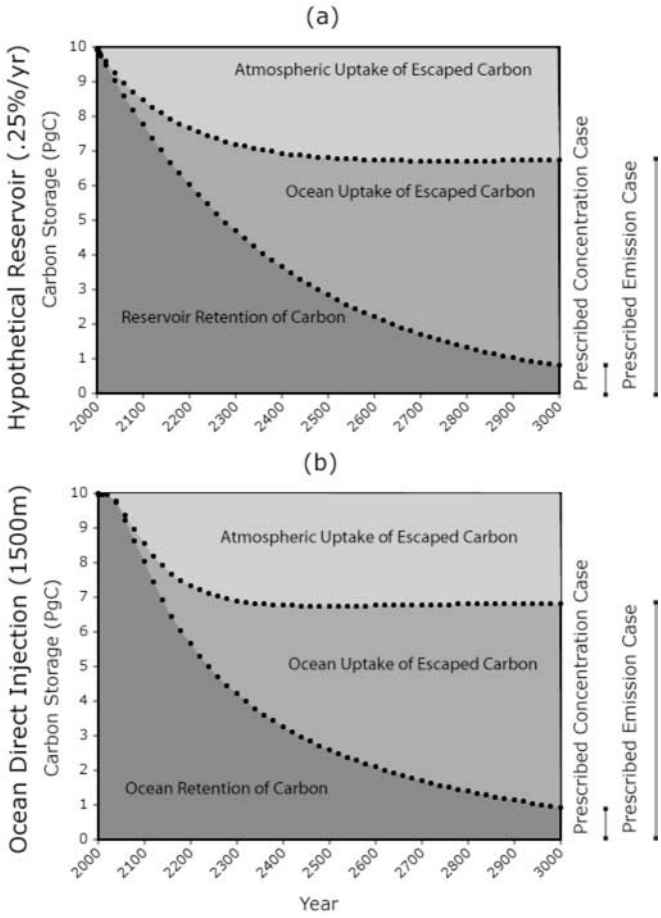

Figure 3. (a) An impulse of 10 PgC was injected into the ocean at depth of 1500 m for the 550 ppm prescribed emission scenario case (EM550). Shown here is the distribution of injected carbon between the initial ocean retention, ocean uptake of leakage, and atmospheric uptake of carbon, as determined by curves representing the prescribed emission and prescribed concentration cases. (b) An impulse of 10 PgC was delivered into a hypothetical reservoir that leaks at a rate of 0.25%/yr for the 550 ppm prescribed emission scenario case (EM550). Shown here is the distribution of delivered carbon between reservoir, atmosphere, and ocean over a thousand-year span.

influence of the terrestrial biosphere was omitted to facilitate comparison).

[19] Figure 3a demonstrates the considerable difference these two methods of accounting the efficacy of the hypothetical reservoir, which are given by two different cases. In the prescribed concentration case, all of the CO_2 stored will eventually leak out of the reservoir, so the equilibrium retention is 0 PgC. If we define the leakage timescale under which this equilibrium is reached as the time at which half of the eventual leakage has occurred, then the leakage timescale is 280 years. In the prescribed emission case, where oceanic absorption of leakage is factored in, the equilibrium retention is 6.9 PgC and the leakage timescale is 65 years. This shortened timescale demonstrates how rapidly the rate of air-sea equilibration overtakes the reservoir leakage rate.

[20] Like the CO_2 from the generic leaky hypothetical reservoir sequestration, the total CO_2 intended for storage may again be divided into three pools over time, (1) the fraction of CO_2 that has not leaked (sometimes referred to as the storage efficiency), (2) the fraction of CO_2 that has leaked into the atmosphere and remains there (sometimes referred to as the airborne fraction), and (3) the fraction of CO_2 that has leaked into the atmosphere and been absorbed/re-absorbed by natural sinks of carbon, most notably the ocean. Figure 3b shows how the above fractions are related to the choice of atmospheric boundary conditions for the modeling of direct injection of 10 PgC into the ocean at a depth of 1500 m. Here, boundary conditions are given by WRE550 and EM550. For the prescribed emission case of direct ocean injection, changes in air-sea flux wrought by the injection are allowed to affect the model-simulated concentration of atmospheric CO_2. The net uptake of CO_2 is thus the sum of initial ocean retention and oceanic re-absorption of carbon leaked to the atmosphere. For the prescribed concentration case the ocean uptake of escaped carbon does not affect the concentration of atmospheric CO_2 and is therefore equivalent to the initial ocean retention of carbon.

[21] Figure 3b demonstrates the considerable significance of oceanic re-absorption for direct injection in precisely the same manner as Figure 3a does for a hypothetical reservoir. In the absence of oceanic re-absorption, the eventual carbon retention of 1500 m direct injection is 0.0 PgC with a leakage timescale of 240 years as simulated by the prescribed concentration case. In the prescribed emission case, where oceanic re-uptake occurs, the role of air-sea equilibration quickly takes prominence just as for the hypothetical reservoir, as evident by the significantly lesser leakage timescale of 110 years in approaching the same equilibrium airborne fraction as the hypothetical reservoir, 0.69 (Figure 3). However, unlike the reservoir, ocean retention of direct injection does not exhibit a pure exponential decay toward equilibrium. First, in both cases, there is a roughly 40-year lag time before significant CO_2 evasion begins to occur, during which time, the injected CO_2 has not yet circulated to outgassing regions of the ocean. Second, in the case of prescribed emissions, the 110-year timescale determined can be misleading because the ocean retention does not exponentially decay toward equilibrium with time. Rather, a minimum retention is reached at 500 years, after which a slow equilibration toward a slightly higher value occurs. One thousand years into the simulation, storage efficiency is 0.1 and still declining while the airborne fraction has already reached a minimum and nearly converged to its asymptotic value of 0.69. The value of this prescribed emission asymptote is governed entirely by sea-surface chemistry. The timescale of approach to asymptote is not. For both the prescribed emission and the prescribed concentration cases, leakage timescale is also highly dependent on modeled ocean physics, depth of injection, and choice of case.

[22] Also relevant to the determination of carbon sequestration effectiveness is the quantity of CO_2 present in the atmosphere during and following the time at which sequestration occurs. Figure 4 shows the simulated ocean carbon retention in response to a 1500-m injection of 10 PgC for three prescribed emission scenarios: EM278, EM550, and

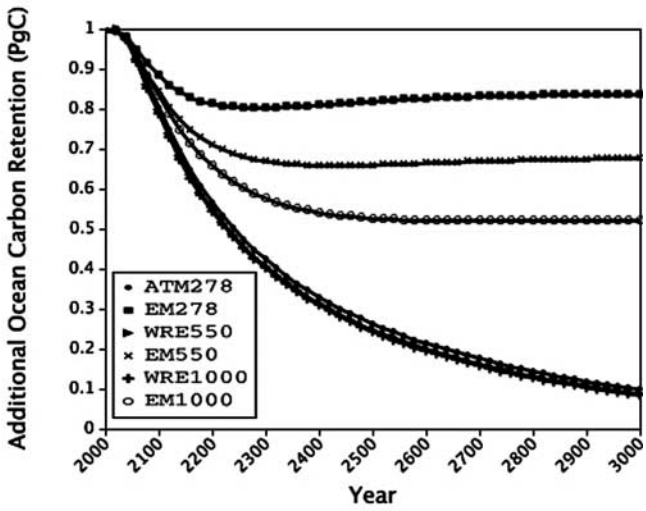

Figure 4. Ocean carbon retention, presented as a fraction of an initial direct injection of 10 PgC at 1500 m depth, determined under three prescribed concentration scenarios, ATM278, WRE550, and WRE1000, and under three corresponding prescribed emission scenarios, EM278, EM550, and EM1000.

EM1000; and for three prescribed concentration scenarios: ATM278, WRE550, and WRE1000. The scenarios EM1000, EM550, and EM278 show ocean retention of 5.4, 6.9, and 8.5 PgC in the year 3000. Higher background surface layer CO_2 partial pressure allows for greater relative increase in oceanic CO_2 partial pressure caused by the injected carbon due to the nonlinearity of surface layer carbonate chemistry. Therefore, for the prescribed emission scenarios, greater quantities of atmospheric CO_2 result in lesser retention of injected carbon in the ocean. This resultant discrepancy in ocean carbon retention under the different scenarios is significant after only 100 years.

[23] In contrast to the prescribed emission case, prescribed concentration cases exhibit low sensitivity to levels of CO_2 in the atmosphere during and following sequestration. Because the atmosphere does not gain the carbon that leaks from the ocean in this case, the differences in air-sea equilibration caused by differences in atmospheric CO_2 do not have a significant effect on long-term ocean retention. Throughout the simulation, the difference between each of the prescribed concentration cases is less than 0.25 PgC. In the year 3000, simulations under each of ATM278, WRE550, and WRE1000, all exhibit retention of 1.0 ± .1 PgC out of the original 10 PgC injection.

7. Conclusions

[24] Careful attention must be paid to choice of background atmospheric CO_2 conditions specified during the simulation of ocean sequestration. Two primary approaches have been used: the prescribed emission case, where levels of atmospheric CO_2 are responsive to changes in air-sea flux caused by the sequestration taking place, and the prescribed concentrations case, where levels of atmospheric CO_2 do not change. There is a wide discrepancy between results obtained under these two cases, generated by the inclusion in the prescribed emission case of leaked carbon re-absorption by the ocean. The effect of this inclusion on simulated retention of carbon kept out of the atmosphere following direct injection is roughly equivalent to the effect of including ocean uptake of leaked carbon for any other sequestration scheme. Furthermore, the sequestration effectiveness determined under the prescribed emission case is highly sensitive to the magnitude of prescribed CO_2 emissions. Effectiveness determined under the prescribed concentration case is, in contrast, largely insensitive to the levels of prescribed atmospheric CO_2 concentrations. However, a more detailed investigation of biogeochemical sensitivity to oceanic CO_2 concentrations (including, for instance, more explicit $CaCO_3$ dissolution chemistry) would be necessary to corroborate this claim. Furthermore, the climate change induced by greater levels of atmospheric CO_2 could certainly significantly influence sequestration effectiveness.

[25] Each approach to the modeling of sequestration has its appropriate application. Experiments performed under the prescribed concentration case are well suited for the determination of ocean sequestration scheme efficiency as it relates to policy analysis because ocean CO_2 reabsorption, a natural process that would occur regardless of the scheme, is discredited. Furthermore, results under this case do not significantly depend on the atmospheric CO_2 scenario chosen and are therefore relevant for a wider range of future scenarios. Prescribed emissions cases are still important for the investigation of issues relating to carbon/climate or land/ocean interactions, because oceanic re-absorption of CO_2, leaked to the atmosphere from the ocean is the true corollary of real world ocean response to sequestration.

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