Assessing the effectiveness of direct injection for ocean carbon sequestration under the influence of climate change

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[1] This paper studies the effect of climate change on simulated efficiency of carbon injection at different locations and ocean depths using an Earth system model of intermediate complexity, ISAM-2.5D. Following the OCMIP carbon sequestration protocol, we carried out a series of carbon injection simulations. The ISAM results show that warming over the next 500 years under the IPCC S650 and WRE1000 stabilization scenarios could change the ocean circulation and thereby increases the residence time of CO_2 disposed into the deep ocean, particularly for Atlantic injection. However, the warming does not have a significant effect on carbon injections into the Pacific and Indian Oceans, where circulation change is small. This new finding contrasts with previous OGCM results. **Citation:** Jain, A. K., and L. Cao (2005), Assessing the effectiveness of direct injection for ocean carbon sequestration under the influence of climate change, *Geophys. Res. Lett.*, *32*, L09609, doi:10.1029/2005GL022818.

1. Introduction

[2] Efforts are being made to reduce our dependence on fossil fuels through improved efficiency and the introduction of non-fossil energy sources [*Hoffert et al.*, 2002]. However, it is becoming clear that current fossil fuel usage patterns are inconsistent with CO_2 stabilization scenarios, even incorporating optimal efficiency improvements and non-fossil energy sources. This has led to increased interest in finding other more economical and realistic measures that can be employed to stabilize the climate. The direct injection of CO_2 emissions generated by power plants in the deep ocean has been proposed as one alternative to control increasing levels of atmospheric CO_2 [*Marchetti*, 1977; *Hoffert et al.*, 2002; *Caldeira et al.*, 2001]. In this control approach, fossil fuel CO_2 is directly injected into the ocean interior, thereby bypassing the slow mixing processes that transfer excess atmospheric CO_2 from the ocean surface into the deep ocean.

[3] Both schematic ocean models [e.g., *Hoffert et al.*, 1979; *Cole et al.*, 1993; *Kheshgi et al.*, 1994; *Mueller et al.*, 2004] and comprehensive 3-D ocean carbon cycle models [e.g., *Nakashiki and Ohsumi*, 1997; *Dewey et al.*, 1997; *Caldeira et al.*, 2001; *Orr et al.*, 2001] have been used to address this issue. However, both modeling approaches commonly neglect two important interactive feedback processes between the ocean climate, carbon cycle and marine biology, which could alter the *long-term* effectiveness of ocean injection. The first of these processes is that the change in atmospheric CO_2 concentrations will alter the pathway of climate change, affecting ocean circulation. This could affect the transport and fate of sequestered carbon in the deep ocean. The second is that ocean carbon sequestration will alter marine biogeochemical cycles, which in turn could influence the efficiency of ocean carbon sequestration.

[4] The purpose of this paper is to study the effect of the first feedback on the efficiency of direct carbon injection using an Earth system model of intermediate complexity, ISAM-2.5D [*Cao and Jain*, 2005]. In particular, we will answer the following questions: How will climate mitigation affect the direct injection of CO_2 in the ocean? Will there be positive, negative, or insignificant feedback between ocean sequestration efficiency and climate change? Which ocean will store more carbon under the climate-changed environment? The answers to these questions are crucial in determining the long-term efficiency of various ocean carbon sequestration strategies in the context of climate change.

2. Model Description

[5] We performed several direct injection of CO_2 experiments as discussed below using the ISAM-2.5D coupled climate-carbon cycle model. The geographic configuration of the model has a latitudinal resolution of 10° with each latitude band divided into one or more ocean and/or land bands in order to resolve major ocean basins and continents. The ISAM-2.5D represents key components of the climate-carbon systems in a fully coupled, consistent system, albeit in a more reduced form compared to 3-D comprehensive models. It includes a zonally averaged multi-basin dynamic ocean module largely based on *Wright and Stocker* [1992] and *Harvey* [1992] but with some modifications such as the use of Gent-McWilliams mixing scheme [*Gent et al.*, 1995] and stability dependent vertical diffusivity [*Hirst and Cai*, 1994], an energy and moisture balance atmosphere module and a land surface module [*Weaver et al.*, 2001], a thermodynamic and dynamic sea ice module [*Semtner*, 1976], a radiative transfer module [*Jain et al.*, 2000], and an ocean carbon cycle module [*Orr et al.*, 1999]. The model is described in detail in [*Cao and Jain,* 2005].

[6] ISAM-2.5D couples the carbon cycle module to radiative forcing, and climate modules to estimate the climate warming and its effect on the CO_2 partial pressure. There are other factors influencing climate (e.g., solar fluctuations, volcanoes) that result in climate variability that is not represented in the ISAM-2.5D simulations. In addition, there is considerable uncertainty in the radiative forcing of climate from, e.g., aerosols [*Schwartz and*

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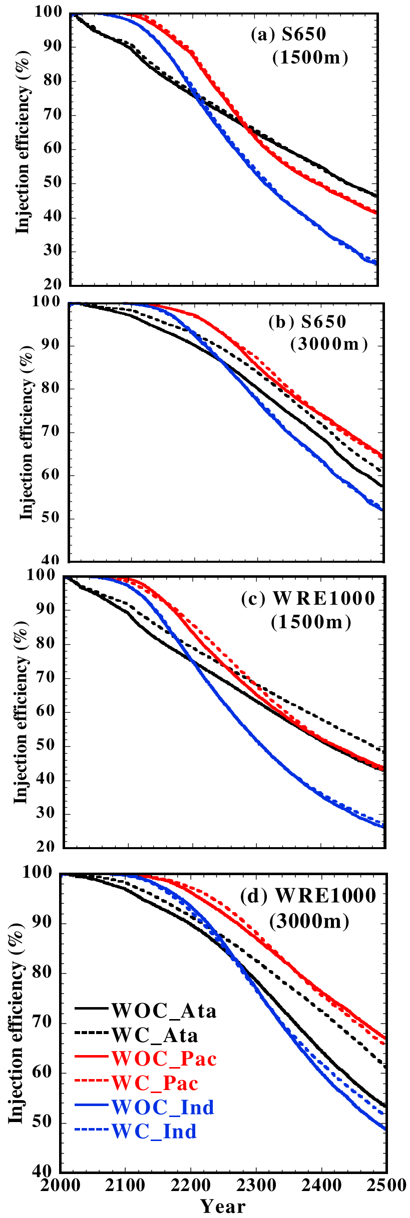

Figure 1. ISAM-2.5D simulated injection efficiency (defined as the ratio of the mass of injected carbon that remains in the ocean to the total injected carbon) for different ocean basins (Ata: Atlantic; Pac: Pacific; Ind: Indian). The calculations are done for with (WC) and without (WOC) climate change cases under S650 and WRE1000 CO2 stabilization scenarios for injection depths of (a) and (c) 1500m and (b) and (d) 3000m.

Andreae, 1996], that are not considered in this study. ISAM-2.5D modeled climate change has the potential to affect carbon uptake through changes in CO_2 solubility, ocean circulation, sea ice cover, and freshwater flux.

[7] ISAM-2.5D is capable of simultaneous simulation of oceanic uptake of heat, freshwater, carbon, and natural and bomb ^{14}C with the Gent-McWilliams parameterizations. The coupled model is driven by the daily average solar insolation at the top of the atmosphere, allowing resolution of a full seasonal cycle. ISAM-2.5D estimated global mean temperature change resulting from a doubling of atmospheric CO_2, defined as climate sensitivity (ΔT2x), is about 2.7°. Compared with 3-D comprehensive models, ISAM-2.5D describes a large set of feedback mechanisms explicitly in the climate system while retaining sufficient computational efficiency to allow long-term climate-ocean-carbon simulations over hundreds to thousands of years.

3. Experiments Performed

[8] The model is first run to steady state with preindustrial (year 1765) atmospheric CO_2 concentrations of 278 ppmv. We then simulate the oceanic uptake of CO_2 over the period 1765–1999 based on the CO_2 concentration from ice cores and direct measurements [*Enting et al.*, 1994; *Keeling and Whorf*, 2000] according to *Cao and Jain* [2005]. Then following Ocean Carbon Cycle Model Intercomparison Project (OCMIP) carbon sequestration protocols [*Orr et al.*, 1999], we perform two sets of carbon sequestration experiments over the period 2000–2500.

3.1. Base Simulations (BS)

[9] In this set of experiments we perform four base model simulations - two with climate change (WC) and two without climate change (WOC) - in which no carbon was injected into the deep ocean. In WC simulations, climate change is allowed to influence the carbon cycle throughout the simulation period, whereas in WOC runs we assume no interaction of climate change with the carbon cycle component of the model. Each two of the BS are run with two different background atmospheric CO_2 stabilization scenarios: (1) IPCC S650 scenario, and (2) IPCC WRE1000 scenario. In these scenarios the atmospheric CO_2 concentrations are stabilized at 650 ppmv and 1000 ppmv. The IPCC S650 scenario is used as a benchmark scenario for the OCMIP protocol. The additional WRE1000 scenario [*Cubasch et al.*, 2001] cases are run here in order to illustrate the effect of potential high CO_2 levels on direct ocean carbon injection.

3.2. Sequestration Simulation (SS)

[10] Same as BS runs, but carbon is injected into the Atlantic, Pacific, and Indian Oceans at depths of 1500 and 3000 m respectively. The approximate injection latitude locations in different oceans are chosen to represent the injection sites given by the OCMIP injection protocol of New York (40–50°N band for the Atlantic), San Francisco (30–40°N band for the Pacific), and Bombay (10–20°N for the Indian Ocean). In each experiment, carbon injection begins in the year 2000 at a rate of 0.1PgC/yr and continues for 100 years until the year 2100. Between 2100 and 2500 no carbon injection is performed.

[11] The injection efficiency for each carbon injection case is determined by the difference in ocean carbon content between BS runs and SS runs. The effect of climate change on carbon injection is examined by comparing the results of WC and WOC experiments.

4. Results

[12] We begin the discussion with the OCMIP benchmark injection simulation, which assumes the IPCC S650 background CO_2 concentration scenario and the injection efficiency was calculated without the effect of climate change.

Table 1. Comparison of ISAM-2.5D and OGCM Estimated Carbon Injection Efficiency (Defined as the Percentage Ratio of the Mass of Injected Carbon That Remains in the Ocean to the Total Injected Carbon) for Different Ocean Basins

	Atlantic		Pacific		Indian	
			2100			
	3000m	1500m	3000m	1500m	3000m	1500m
WOC_S650[a]	97	89	99	99	99	98
WC_S650[b]	98	91	99	99	99	98
WOC_WRE1000[a]	97	89	99	99	99	97
WC_WRE1000[b]	98	92	99	99	99	97
Orr et al. [2001][c]	96–98	50–98	98–99	97–99	96–99	84–99
			2500			
WOC_S650[a]	56	45	64	41	52	26
WC_S650[b]	61	46	64	42	52	26
WOC_WRE1000[a]	53	43	66	43	49	26
WC_WRE1000[b]	61	48	65	43	51	26
Orr et al. [2001][c]	52–90	18–42	62–90	32–76	36–96	28–58

[a]Without climate change.
[b]With climate change.
[c]Based on seven OGCM and one zonally averaged model results, which are based on S650 background CO_2 concentration scenario and do not consider climate change effect.

It can be seen that the deeper the injection, the less leakage of the injected amount (Figures 1a and 1b). The model predicted injection efficiency in different ocean basins at 3000m after the end of the 100-year injection (year 2100) ranges between 97 and 99%; which reduces to 52 and 64% after 500 years (year 2500). On the other hand, the model estimated injection efficiency at 1500m ranges between 89 to 99% in the year 2100, and 26 to 45% in the year 2500. These results are largely comparable with the injection efficiency simulated by a number of OGCMs (Table 1) [*Orr et al.*, 2001].

[13] In terms of inter-basin comparison, ISAM-2.5D simulated injection is most efficient in the Pacific Ocean throughout the simulation period for 3000 m injection cases (Figure 1b). By the year 2500, the Pacific holds about 64% of the injected carbon, whereas the Atlantic Ocean holds about 56%. However, for the 1500 m injection the Pacific holds more carbon until the year 2300. Thereafter, the Atlantic Ocean displays higher injection efficiency (Figure 1a). It is worth mentioning here that there is no agreement between different OGCM results as to which ocean would be more efficient in retaining injected carbon. For example, *Dewey et al.* [1997] and *Archer et al.* [1998] found that injection in the Atlantic Ocean would be more effective than injection in the Pacific Ocean, but results reported by *Caldeira et al.* [2001] and *Orr et al.* [2001] indicate that the reverse is true. This issue is beyond the scope of this paper and needs to be further investigated using a variety of models.

[14] Our model results indicate that the changes in background atmospheric CO_2 concentration under constant climate conditions do not significantly influence the injection efficiencies (Table 1). These small differences in injection efficiency are caused by the nonlinear response of ocean carbonate chemistry to changes in atmospheric CO_2 concentrations.

[15] Next, we investigate the effect of climate change on simulated efficiency of carbon injection. Among S650 background scenario simulations, the effect of climate change is most pronounced in the Atlantic Ocean for the 3000m injection case (Figure 1b). The simulated injection efficiency throughout the simulation period is larger for the WC case than that for the WOC case, with the efficiency increasing from 56% to 61% by the year 2500 (Table 1 and Figure 1b). This increase in injection efficiency is attributed to the slowdown of the thermohaline circulation (THC) in the Atlantic Ocean caused by global warming. CO_2-induced global warming increases both the heat and freshwater fluxes of the high latitude ocean, and thus decreases surface ocean density, which results in a weakened North Atlantic Deep Water (NADW) formation and a shallower NADW downward penetration. Based on our model simulation, the maximum intensity of the NADW formation is reduced by about 3Sv (1Sv = 10^6 m^3 s^{-1}) under the S650 scenario. The weakened strength and reduced downward penetration of the NADW allow a stronger northward intrusion of the Antarctic Bottom Water (AABW) into the Atlantic Ocean. With a slowdown of the NADW formation, overall Atlantic Ocean circulation reduces over the period 2000–2500, with the largest reduction in the deep ocean at about 4000m (Figure 2a). The reduced overturning causes less injected carbon to be brought back to the ocean surface through upwelling, and thus enhances injection efficiency. Moreover, the climate change effect is negligible for the 1500 m injection (Figure 1a) due to smaller circulation changes in the upper ocean. Climate change has almost negligible effects on the Pacific and Indian Ocean injection efficiencies at all depths. This is because no significant changes in ocean circulation occur in both the Pacific and Indian Oceans in our model (Figure 2).

[16] Relative to the S650 cases, climate change has larger influences on injection efficiencies for simulations under the WRE1000 scenario, especially for the Atlantic Ocean (Figures 1c and 1d). For the 3000m depth injection, climate

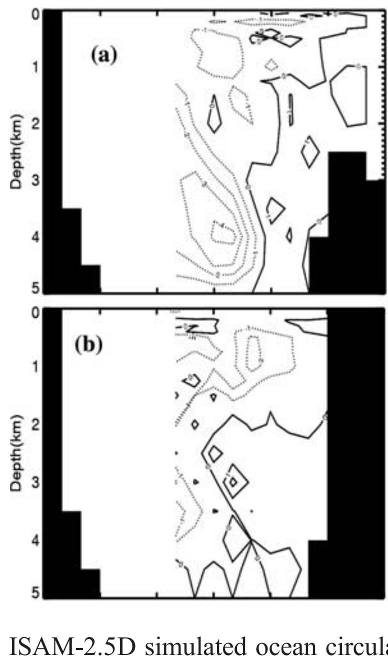

Figure 2. ISAM-2.5D simulated ocean circulation change (Sv, 1Sv = 10^6 m^3 s^{-1}) between year 2000 and 2500 for the (a) Atlantic and (b) Pacific Oceans under the S650 CO_2 stabilization scenario. Results for the Indian Ocean are not shown here since the circulation change is negligible.

change increases efficiency by about 8% by the year 2500 (from 53% for the WC case to 61% for the WOC case) (Figure 1d), which is about a 4% greater increase than that based on the S650 experiments (Figure 1b). For the 1500m depth injection, climate change increases injection efficiency by about 5% by the year 2500 (from 43% for the WOC case to 48% for the WC case) under the WRE1000 background scenario (Figure 1c), compared to negligible changes under the S650 scenario (Figure 1a). The larger effect of climate change on simulated injection efficiency is a direct result of larger circulation change under the WRE1000 scenario. Again, the effect of climate change is small on injections in both the Pacific and Indian Oceans because of small circulation changes in these two basins.

5. Discussion and Conclusions

[17] A set of ocean carbon injection experiments was performed using an Earth system model of intermediate complexity, ISAM-2.5D. Our model results suggest that climate change increases the retention time of injected carbon in the Atlantic Ocean, whereas climate change has no significant effect on the retention time of injected carbon in the Indian and Pacific Oceans. As a result, when climate change is included, CO_2 injected into the deep Atlantic Ocean may be retained longer than into the deep Indian and Pacific Oceans. However, based on a variety of model simulations [*Cubasch et al.*, 2001], a large uncertainty exists regarding the extent of the Atlantic thermohaline circulation change under global warming scenarios. Our simulation yields a modest circulation change even under the WRE1000 scenario (a maximum reduction of about 5Sv in the NADW formation). However, some modeling results show a much larger reduction in the Atlantic THC, with the extreme case of a collapse of the NADW formation in some global warming experiments [e.g., *Manabe and Stouffer*, 1994; *Schmittner and Stocker*, 1999; *Joos et al.*, 1999]. Our study suggests that carbon injection efficiency would be greatly enhanced under this extreme case, particularly in the deep Atlantic Ocean.

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