MODELING THE OCEANIC STORAGE OF FOSSIL FUEL EMISSIONS

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KEYWORDS: global carbon cycle, ocean disposal, fossil fuel emissions

ABSTRACT

We use the GLOCO model to analyze the potential for oceanic storage of carbon dioxide emissions from fossil fuel combustion, as well as the effect on atmospheric CO_2 (pCO_2) concentration. From a sensitivity analysis of the global carbon cycle, we find that the rate of transport of carbon to the deepest oceanic layers is rather insensitive to the atmospheric-ocean surface gas exchange coefficient, but to a larger extent on the upwelling velocity. The location of the carbon emissions, whether they are released in the atmosphere or in the middle of the oceanic thermocline, has a significant impact on the maximum pCO_2 subsequently reached, suggesting that oceanic burial of a significant fraction of carbon emissions (e.g. via clathrate hydrides) may be an important management option for limiting pCO_2 buildup. The effectiveness of ocean burial decreases asymptotically below about 1000 m depth, considering a one-dimensional ocean model, i.e. perfect mixing at the various ocean levels where the carbon is injected. With a constant emissions scenario (at 1990 levels), pCO_2 rises to 501 ppmv by the year 2100 if all the emissions go to the atmosphere. With ocean burial of 50% of the fossil fuel emissions at a depth of 1000 m, pCO_2 rises only to 422 ppmv. An alternative scenario looks at stabilizing pCO_2 at 450 ppmv; with no ocean burial of fossil fuel emissions, the rate of emissions has to be cut drastically after the year 2010, whereas oceanic burial of 2 GtC/yr allows for a smoother transition to alternative energy sources.

INTRODUCTION

Capturing carbon dioxide emissions at the smokestack and injecting them into the ocean has been proposed by Marchetti (1977), Hoffert *et al.* (1979), Liro *et al.*(1992), Golomb *et al.*(1992), Kheshgi *et al.*(1994) and others. These previous studies have relied on simple oceanic box models, and have mostly been used to analyze the response of a pulse injection rather than the projected ramp increases in anthropogenic carbon dioxide emissions due to fossil fuel combustion, and neglecting the impact of carbon storage in terrestrial biomes in both the transient and equilibrium carbon cycle response.

For this analysis, we use the GLOCO model (Hudson *et al.*, 1994), a global carbon cycle model with a mechanistic description of physical and biogeochemical processes in the terrestrial biomes and oceans. The model considers eight terrestrial biomes, two oceans (high and low latitude, each broken further into surface and deep layers) and one well-mixed atmosphere. Complete atmospheric mixing is assumed since the model's time step is one year. The model allows the input of different anthropogenic carbon emissions (CO_2 and CH_4), from industrial as well as agricultural and forestry activities (including land-use changes). Temperature of each biome or ocean can be independently modeled as a function of atmospheric CO_2 concentration.

The oceanic carbon cycle model used in GLOCO is based on the HILDA model (Siegenthaler and Joos, 1992), an outcrop-diffusion model. In addition to discerning between high and low latitude oceans, the model has a significant spatial resolution in the vertical direction, with 68 layers of deep low-latitude ocean. Chemical equilibrium controls the final distribution of carbon. GLOCO considers the dissociation of water, carbonic, boric and dissolved organic carbon-based acids, as well as the assimilation of carbon to particulate organic carbon (POC) and dissolved organic carbon (DOC), deposition of calcium carbonate in sediments and remineralization of POC and DOC. Each layer is considered to reach equilibrium rapidly, but due to transport limitations, the system as a whole can take thousands of years to achieve equilibrium once it is perturbed. The non-linear chemical equilibrium is coupled with convection-diffusion processes. Carbon is also transported downward to the deep ocean by the oceanic "biological pump".

The terrestrial biome models are based on a generic biome module describing photosynthesis, respiration and growth by vegetation, and microbial decomposition of plant litter and soil organic matter, with parameter values for each biome: temperate, boreal and tropical forests, grasslands, woodlands, tundra, deserts and agriculture. Carbon and nitrogen are cycled within the biome; these nutrients are allocated to the various plant tissues, and the fluxes of carbon and nitrogen in and out of the biome are considered. The rates of the biological processes are temperature dependent, to incorporate the effect of potential temperature rise in the coming centuries.

We assume that the carbon dioxide from fossil fuel combustion would be injected as a clathrate hydrate, which has been shown (Sakai *et al.*, 1990; Saji *et al.*, 1992) to form a stable phase at the pressure, temperature and salinity of the deep ocean (>500 m). Our analysis has two major assumptions. First, we assume that the injected clathrate dissolves and mixes completely and instantaneously at the depth it is injected in the low-latitude ocean. In fact, the clathrate should sink, due to the higher density of the clathrate hydrate relative to the surrounding water, and the clathrate phase should be even more stable at greater depths. Our second simplification is to neglect calcite dissolution in the bottom waters of the ocean which is expected to result in additional long term storage of carbon (Hoffert *et al.*, 1979; De Baar, 1992). Our simplifications are overall conservative and would tend to understate the additional storage of carbon in the deep ocean. The assumption that mixing at the injection depth is instantaneous may be conservative or not depending on the local water transport, i.e. upwelling or downwelling.

SENSITIVITY OF OCEAN TRANSPORT PARAMETERS

Considering that most of the carbon emitted to the atmosphere will eventually end up in the oceans (Keller and Goldstein, 1994), and that the approach to equilibrium is constrained mostly by oceanic physical transport, we sought to determine how important was the choice of ocean transport parameter values to reaching equilibrium. For example, there are a number of studies on the atmosphere-ocean gas-exchange coefficient (Robertson and Watson, 1992; Broecker and Maier-Reimer, 1992; Stanton, 1991; Volk and Bacastow, 1989), and its spatial and temporal variability (Etcheto *et al.*, 1991; Erickson, 1989). Values of the gas-exchange coefficient vary by more than an order of magnitude. How significant is this in terms of our analysis?

Another important parameter is the upwelling velocity of deep water in lower latitudes. Upwelling brings cold, nutrient rich water to the surface, and thus a larger upwelling velocity may increase the rate of oceanic net primary productivity, increasing the flux of carbon to DOC and sediment pools (Bacastow and Maier-Reimer, 1991; Baes and Killough, 1986) resulting in a larger carbon storage. In addition, from a mass balance on water, a larger upwelling velocity would result in a larger downward water flux at higher latitudes, carrying carbon-enriched surface waters to greater depth.

The parameter values used in the calibration of the GLOCO model correspond to those in the oceanic HILDA model, which has been used to study the distribution of radioactive tracers, matching the measured concentration profiles adequately. Given the variability in the published values of these two transport parameters, we studied the effect of increasing or decreasing them by an order of magnitude, which covers more than the published variability in parameter values. A pulse of 594 Gt C is instantaneously released in the atmosphere, to simulate a doubling of the atmospheric CO_2 (pCO_2) from its preindustrial value, and then the system is allowed to relax to a new equilibrium situation. The effect on pCO_2 is presented in Figure 1. The base case considers the calibration parameter values for GLOCO.

Increasing or decreasing the gas-exchange coefficient by a factor of 10 has very little impact on the rate at which equilibrium is reached. If the gas-exchange rate is increased by a factor of 10, there is virtually no change in the pCO_2 profile, when compared with the base case. Analyzing the profiles of dissolved inorganic carbon (DIC) in the ocean, we observe that only the top ocean layers, above the thermocline, are affected, and only by a small amount. Reducing the resistance of gas transfer to the surface of the ocean does not significantly increase the overall rate of carbon storage in the ocean because it is limited by downward transport. And the additional carbon in the surface waters does not result in additional uptake as DOC or POC, since carbon is not the limiting nutrient. The atmospheric response is slightly larger for the case where the gas-exchange coefficient is reduced by a factor of 10. In this case, the resistance to gas transfer does result in slightly larger atmospheric concentrations, in particular at early times. As expected, the equilibrium atmospheric concentration is the same for all cases.

If our current estimate of the upwelling velocity was off by a factor of 10, the impact on our predictions of future pCO_2 would be important only in the case of much greater upwelling velocities. If the upwelling velocity was $1/10^{th}$ of our current estimate, the effect would be minimal in terms of our pCO_2 predictions. However, an actual upwelling velocity ten times larger than our current estimates would result in significant increase in carbon storage both in DOC and sediments. Given that oceanic carbon storage would increase, the equilibrium would shift and less carbon would then be stored in the terrestrial biomes, as well as in the atmosphere. The net reduction in total carbon stored in the atmosphere is on the order of 35 Gt C. The impact is greatest at larger times (>200 years).

OCEAN BURIAL OF CARBON FROM FOSSIL FUEL COMBUSTION

If the same 594 Gt C pulse is injected into the ocean at a depth of 500 m as DIC, considering the calibration transport parameter values, the global carbon cycle approaches equilibrium relatively fast, redistributing carbon in the ocean, and releasing carbon to the atmosphere (Figure 1). In less than two hundred years, pCO_2 practically reaches its equilibrium value. There is no change in DOC or oceanic carbon sedimentation rates, and the approach to equilibrium is actually only delayed by the terrestrial biome uptake of the incremental atmospheric carbon. In effect, we have "bought" a delay of about 200 years in the maximum pCO_2 by burying the fossil fuel emissions at a depth of 500 m. What is the effect of burying the emissions at different depths? Can we have a bigger impact by injecting at deeper levels? And at what point does this approach become less effective?

Considering the same pulse (a 2x carbon pulse, based on the preindustrial atmospheric concentration), we studied the effect on pCO_2 of injecting at deeper ocean levels (Figure 2). All the atmospheric CO_2 profiles approach the same equilibrium value of around 325 ppmv after 750 years. However, the maximum pCO_2 is reached much later depending on the injection depth. And the maximum pCO_2 is lower as we increase the injection depth (Figure 3). We can continue to inject at lower and lower depths, but this analysis suggests that going deeper than 1500 m is not effective in terms of reducing the maximum pCO_2, since we reach an asymptotic value. In fact, it may be argued that the difference in the maximum pCO_2 between injecting at 1000 m and injecting at 1500 m, of less than 8 ppmv, does not justify the larger expense of injecting the carbon 500 m deeper.

Studying the response of the global carbon cycle to a pulse injection is useful because it is easier to compare among models, without the added complexity of varying scenarios. However, the real perturbation to the global carbon cycle is not an instantaneous pulse but rather a continuous increase in anthropogenic carbon emissions to the atmosphere. Currently the system has already been perturbed significantly from its preindustrial levels, so that if we suddenly stopped all anthropogenic emissions to the atmosphere, the system would relax to a new equilibrium position. We studied three potential carbon emissions scenarios. The first involves achieving the current target of voluntarily limiting carbon emissions to their 1990 levels for all nations. The second carbon emissions scenario is the IPCC 92a scenario (Business as Usual). The third scenario looks at limiting carbon emissions such that pCO_2 stabilizes at 450 ppmv. To achieve the stabilization goal, carbon emissions from fossil fuel combustion and land use changes have to be drastically reduced in the next century. Whether we can make the transition to this lower rate of emissions is not entirely clear. Ocean burial of some of the emissions would make the transition easier, by providing some additional time for all nations to switch to either renewable or non-fossil fuel based energy sources.

In Figure 4 we present the result of the first scenario, i.e. carbon emissions at constant 1990 levels. Even with this lofty goal, pCO_2 rises from 354 ppmv in 1990 to 525 ppmv by the year 2100, or 48%. As we increase the fraction of the emissions that is buried in the ocean at a depth of 1000 m, beginning in the year 2000, the maximum pCO_2 by the year 2100 drops significantly. The technology for ocean burial is not in place to begin capturing, transporting and injecting carbon into the ocean by the year 2000, and significant additional modeling with a three-dimensional ocean model must be done before we know where the injection points may be, but this analysis indicates that there may be considerable reduction in the growth of pCO_2 in the future, by burying a fraction of the emissions directly in the ocean.

What if there is no action to reduce carbon emissions, and they grow as projected by the Business as Usual scenario of the IPCC? GLOCO projects a doubling of pCO_2 by the year 2100, to more than 700 ppmv (Figures 5a, 5b). If we followed the same emissions trajectory, but then decided that we should put an arbitrary cap on the maximum pCO_2 of 450 ppmv, as suggested by the 1994 IPCC modeling exercise (Enting et al., 1994) how long could we continue on the Business as Usual trajectory? And what would have to be the needed reduction in carbon emissions to reach the 450 ppmv cap? In Figure 5a we present the fossil fuel emissions trajectory obtained by inversing the GLOCO model. We could maintain the Business as Usual trajectory until the year 2010, at which time we would have to drastically reduce emissions from 8 GtC/yr to around 1 GtC/yr by 2060. The resulting

pCO_2 profile is shown in Figure 5b. If by the year 2010 we had implemented the technologies needed for burying 2 GtC/yr directly into the ocean at a depth of 1000 m, then we could add this level of fossil fuel emissions (2 GtC/yr) to the drastic carbon emissions trajectory, buying some time for the implementation of other energy sources, and making a wiser use of our fossil fuels (Figure 5a and 5b).

CONCLUSIONS

We have analyzed the sensitivity of the GLOCO model, a global carbon cycle model, to two major oceanic transport parameters. The actual value of the globally averaged gas-exchange coefficient is not well known, but our analysis suggest that in terms of the rate of carbon storage in the ocean, the model is rather insensitive to the value of this parameter, even if our calibration value is off by a factor of 10. The transport of carbon into the deep ocean is not controlled by the air-sea gas exchange.

If the upwelling velocity was much lower than our current estimates, it would also have only a minor effect on the global carbon cycle. However, if the actual value was 10 times larger than the current estimate, then the equilibrium would shift, due to upwelling of nutrients to the surface, resulting in a larger DOC pool and greater rates of sedimentation. The larger carbon storage in the ocean would be offset by a reduction in carbon in both the terrestrial biomes and the atmosphere. This indicates that further research should be directed towards understanding the globally-averaged value of the upwelling velocity.

Using the GLOCO model, we studied the effect of disposing some of the anthropogenic carbon emissions directly into the ocean, possibly as clathrate hydrides. Injection of carbon into the deep ocean becomes less and less effective, in terms of the maximum atmospheric CO_2 observed, suggesting that the optimal depth is somewhere around 1000 m.

If we take no action to reduce fossil fuel emissions (IPCC 92a case), then pCO_2 will more than double by the end of the next century, Even if we constrain emissions to their 1990 levels for the next 110 years, we can expect a rise of around 48% in pCO_2 levels. Burying a fraction of the emissions deep in the ocean would reduce the rate of increase in pCO_2 and thus the potential for an increased greenhouse effect and its implications. Public pressure, as well as political pressure from interested parties (e. g. insurance companies) may result in capping pCO_2 to a fixed level, for example 450 ppmv. This would result in significant reductions in combustion of fossil fuel in a relatively short amount of time. Burying a fraction of the emissions would provide some relief, and would allow for a smoother transition to alternative energies.

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Figure 1. Time dependent atmospheric carbon response due to an instantaneous pulse of 594 GtC, for various oceanic transport parameter values, compared to the base case (calibration values and pulse in the atmosphere).

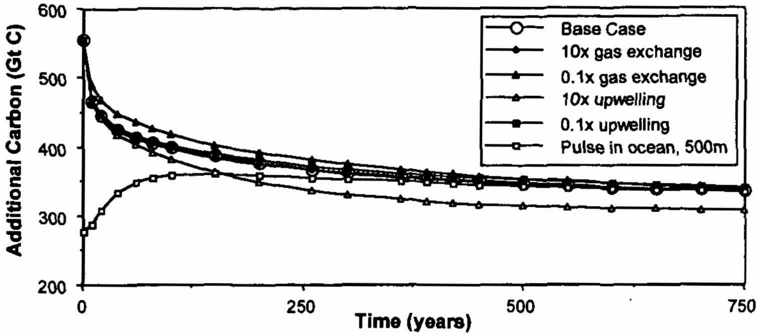

Figure 2. Atmospheric concentration (pCO_2) profiles after the injection of an instantaneous pulse of 594 Gt C directly to the atmosphere (base case) or at various depths in the low-latitude ocean.

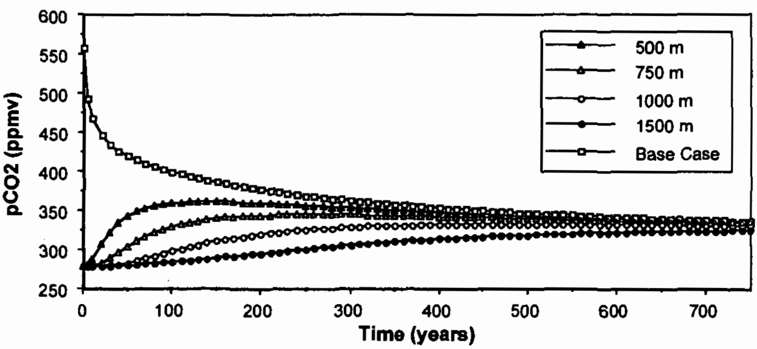

Figure 3. Maximum pCO_2 predicted during the 750 years of simulation as a function of low-latitude ocean burial depth.

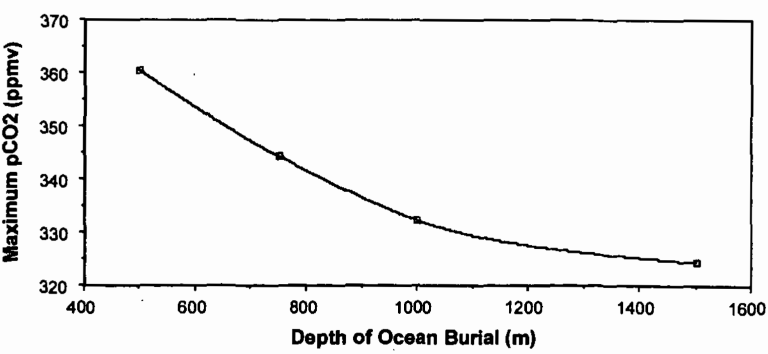

Figure 4. Atmospheric concentration (pCO_2) profiles for a *constant emissions scenario* at 1990 levels, considering direct emission to the atmosphere or increasing oceanic burial.

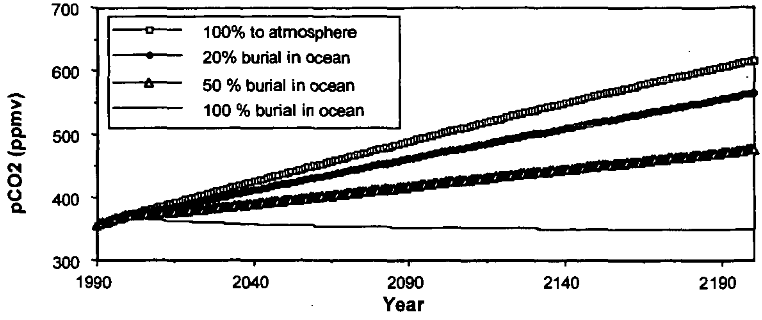

Figure 5a. Carbon emissions from combustion of fossil fuels considering the IPCC 92a Business as Usual scenario and two control scenarios aimed at achieving a stable pCO_2 of 450ppmv with and without ocean burial of emissions.

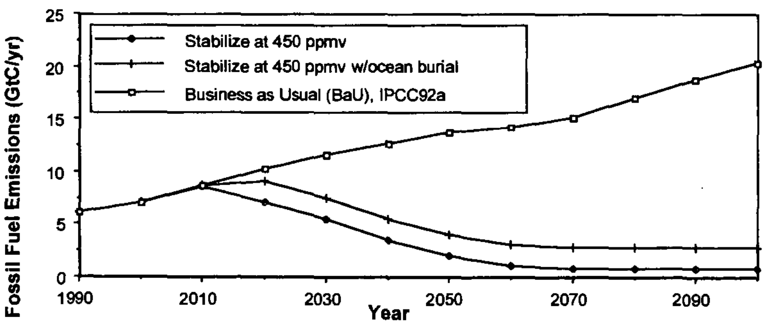

Figure 5b. Atmospheric concentration (pCO_2) profiles for the Business as Usual scenario and the two control scenarios targeting a *maximum* pCO_2 of 450 ppmv.