THE GOSAC PROJECT TO PREDICT THE EFFICIENCY OF OCEAN CO_2 SEQUESTRATION USING 3-D OCEAN MODELS

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ABSTRACT

To evaluate the efficiency of the ocean in retaining purposefully sequestered CO_2, eight ocean modeling groups made a set of standard injection simulations. Injection was made simultaneously at seven separate sites; separate 7-site simulations were made for injection at 800 m, 1500 m, and 3000 m. For injection at 3000 m, all models showed 85% or greater global efficiency in year 2200, i.e., 100 years after the end of the specified 100-year injection period; at the same time, the 1500-m injection is 60-80% efficient and 800-m injection is only 42-61% efficient. Most of the CO_2 injected at 3000 m was lost from the Southern Ocean (the principal region by which the deep ocean is ventilated); at shallower depths, relatively more was lost sooner, from the northern hemisphere and the tropics. The simulated global injection efficiency at 3000 m is correlated with both the simulated global mean CFC-11 inventory and deep-ocean natural ^{14}C. Based on these correlations, the global observational constraints for these two tracers, and model diversity, it appears likely that the range of model-predicted efficiencies would bracket real ocean behavior under the same 3000-m injection scenario.

INTRODUCTION

A quarter of a century ago, it was proposed that one could help limit increases in atmospheric CO_2 by diverting CO_2 emissions from near-coastal power plants into the deep sea [1]. However, uncertainty remains concerning the science of such a strategy. A fundamental question is, how efficient would the ocean be in retaining purposefully sequestered CO_2? Ocean models offer the only quantitative means to answer this question due to the century time scales involved for deep-ocean circulation. Simple ocean box models have been used to provide estimates of the ocean's mean retention efficiency [2]. Simulations with 3-D models can distinguish site-specific efficiencies. However until recently, only one 3-D model had been used for such studies and thus uncertainties had not been addressed. That changed with the initiation of the GOSAC project (Global Ocean Storage of Anthropogenic Carbon). Here we describe results from that project where standard simulations in seven different 3-dimensional global ocean models and one 2.5-dimensional zonal basin average model were systematically compared to provide measures of uncertainty about the ocean's efficiency at retaining purposefully injected CO_2.

Previously, we quantified global and site efficiencies for deep injection [3]. For example, the 3000-m injection is 85% or more efficient in all models in year 2200. At the same year, 1500-m injection is 60-80% efficient and 800-m injection is 42-61% efficient. We further showed that injection at 1500 m was most efficient at sites in the Pacific Ocean (San Francisco, Tokyo) and least efficient at sites in the Atlantic Ocean (New York, Bay of Biscay, and Rio de Janeiro). Here we outline why the most and least efficient sites differ, provide details about the 300-m injection, and assess if simulated global efficiencies are realistic.

MODELS AND SIMULATIONS

The eight global ocean models used in this project have been described previously [3,4]. All models were first integrated to reach a steady state, equivalent to a preindustrial state with atmospheric pCO_2 at 278 ppm. Then the models were forced to follow observed atmospheric CO_2 during years 1765-2000. Subsequently during 2000-2500, models followed IPCC future scenario S650, which eventually stabilizes atmospheric pCO_2 at 650 ppm. Injection occurred only during years 2000-2100, with 0.1 Pg C year^{-1} (1 Pg C = 10^{15} g) injected offshore at each of seven sites (Bay of Biscay, Bombay, Jakarta, New York, Rio de Janeiro, San Francisco, and Tokyo). For each injection simulation, we used a separate tracer to track the each site's injected DIC plume. Nonlinearities due to this multi-tracer approach are negligible [5]. These standard injection simulations are further detailed elsewhere [3], with protocols at http://www.ipsl.jussieu.fr/OCMIP.

RESULTS

For 1500-m injection San Francisco was generally the most efficient site and New York was the least efficient. Much of CO_2 injected at 1500 m at New York was transported northward by the lower part of the Gulf Stream to the North Atlantic in the Norwegian and Greenland Seas. There it was brought back to the surface by deep winter mixing, where it could exchange with the atmosphere. In the North Pacific, some of the injected CO_2 escaped back to atmosphere in the North Polar subpolar gyre. Yet, winter convection in the North Pacific is shallower and less intense than in the Atlantic, thereby explaining its improved efficiency. The efficiency of the Rio de Janeiro site varies most among between models. As most of the CO_2 injected at this location is lost in the Southern Ocean, this large predicted range reflects the large discrepancies between models in this region.

Injection at 3000 m resulted in smaller differences between site efficiencies for a given model. The southern hemisphere sites (Rio de Janeiro and Jakarta) were generally the least efficient. The New York site efficiency improved dramatically, relative to the 1500-m injection, because the plume took a longer pathway to the surface by moving southward to the Southern Ocean. In the 3000-m injection simulation, all sites lost most of their injected CO_2 south of 30?S (Fig. 1) even though five of the seven injection sites are located in the Northern Hemisphere; conversely, around half of CO_2 from both shallower injections was lost from the northern hemisphere. With time, ocean mixing homogenized the distribution of injected CO_2 in the deep-ocean, thereby enhancing loss from the Southern Ocean, which dominates deep-water ventilation in all the models. Although the southern region occupies about 31% of the surface area of the global ocean, loss is enhanced there owing to generally more efficient surface-deep water exchange.

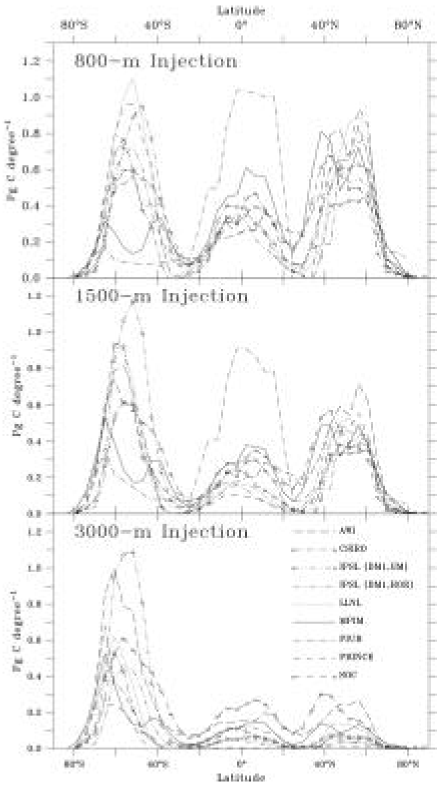

Figure 1: Zonal integral, cumulative loss of injected CO_2 from ocean to the atmosphere (Pg C degree^{-1})

DISCUSSION

Comparison of simulated vs. observed ocean tracers provides a benchmark of model performance that helps to weigh model predictions. Radiocarbon has been measured extensively and its radioactive decay helps us assess the rate at which deep waters are ventilated. This ventilation rate may be related to injection efficiency. The group of models used in this study includes those that have deep waters that are too old to those that have deep waters that are too young. Therefore it would seem likely for the range of results to bracket the real behavior of the global ocean, if purposeful CO_2 injection were actually carried out under the same scenario at 3000 m. Furthermore, natural C-14 and injection efficiency are correlated. For the 3000-m injection, the correlation has an R^2 of 0.57 (Fig. 2). The correlation is lower for the 1500-m injection and there is no correlation for the 800-m injection.

Additionally, there is strong correlation (R^2 = 0.81) between the global inventory of another tracer, CFC-11, and the global efficiency of the 3000-m injection (Fig. 2a). Conversely, there is no correlation with the global CFC-11 inventory for 800-m injection and only a slight correlation (R^2 = 0:31) for the 1500-m injection. Although, we expected to find some correlation with natural ^{14}C, a tracer of deep-ocean circulation, CFC-11 is a man-made transient tracer that only started being released to the atmosphere in the 1930's. The correlation of the 3000-m injection efficiency with the global uptake of CFC-11 (R^2 = 0.81) is even stronger than it is for natural ^{14}C (R^2 = 0.57). One reason may be that surface-to-deep ocean exchange limits CFC uptake as well as loss of injected CO2 to the atmosphere. Further, most of this CFC-11 uptake and most of the loss of CO_2 injected at 3000 m occur in the Southern Ocean. Another reason is that both CFC-11 and injected CO_2 are transient tracers, and natural ^{14}C is not a transient tracer. The transient tracer argument by itself does not explain the increase in correlation with injection depth, but it does seem to help explain the better correlation of the 3000-m injection efficiency with CFC-11 than with natural ^{14}C.

The observational constraint for the global mean ^{14}C below 1000 m is about -150 permil [6], and the model results bracket -150 permil. There is not yet an observational constraint for the global inventory for CFC-11; however, the OCMIP-2 CFC-11 model-data comparison along available sections suggests that the models also bracket the CFC-11 observations. Therefore based on these observational constraints and correlations from two tracers, the range of GOSAC/OCMIP-2 simulated efficiencies for the 3000-m injection would be likely to bracket real ocean behavior given the same injection scenario.

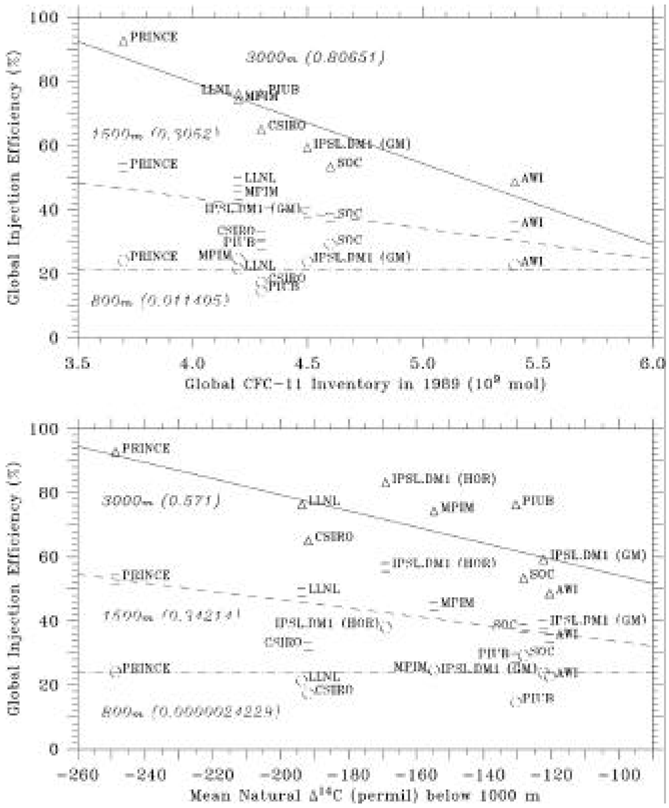

Figure 2: Comparison of the simulated global efficiencies in year 2500 for injection at 800 m (dash-dot), 1500 m (dash) and 3000 m (solid) vs. simulated CFC-11 and 14 C. The R^2 is given in parentheses with corresponding depths in italics for CFC-11 (top panel) and natural ^{14}C below 1000 m (bottom panel).

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REFERENCES

1. Marchetti, C. (1977), *Climatic Change* **1**, 59-68.
2. Hoffert, M.I., Wey, Y.-C., Callegari, A.J., and Broecker, W.S. (1979), *Climatic Change* **2**, 53--68.
3. Orr, J. C., Aumont, O., Yool, A., Plattner, K. Joos, F., Maier-Reimer, E., Weirig, M.-F., Schlitzer, R., Caldeira, K. Wickett, M., and Matear, R. (2001). In: *Proceed. Fifth Int. Conf. on Greenhouse Gas Control Tech.*, pp. 469–474, CSIRO, Collingwood, Australia.
4. Dutay, J.-C., et al. (2002). *Ocean Modelling* **4**, 89–120.
5. Orr, J.C. and Aumont O. (1999), In: *Greenhouse Gas Control Technologies*, pp. 281-286, Eliasson BE, Reimer, P., and Wokaun A., Elsevier, Oxford.
6. Toggweiler, J. R., Dixon, K. and K. Bryan (1989). *J. Geophys. Res.* **94**, 8217–8242.