NARROWING THE UNCERTAINTY FOR DEEP-OCEAN INJECTION EFFICIENCY

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ABSTRACT

Only ocean models can predict how efficient the ocean is in sequestering CO_2 by direct injection. Data is not available to directly evaluate model results in this regard, due to the century time scales required for the deep ocean waters to mix and be brought back to the surface. Ten ocean general circulation models (OGCM) have been compared within the framework of an international project to obtain site-specific efficiencies and corresponding uncertainties. Here we show that across the range of models there is a correlation between global injection efficiency and global metrics for CFC-11, natural ^{14}C, and bomb ^{14}C. These correlations provide support for using these global tracer metrics to help narrow the uncertainty range for the 3000-m injection efficiency. After rejecting the models that do not meet these global tracer criteria, the range in efficiencies becomes four times narrower, dropping from 71±22% to 70±6% in year 2500.

INTRODUCTION

Typically several centuries would be needed for CO_2 that was injected into the deep ocean [1] to be transported laterally and brought back to the surface where it could be exchanged with the atmosphere [2]. Thus global ocean models provide the only framework to quantify the efficiency of the ocean in retaining injected CO_2. Previous comparison of 10 three-dimensional ocean models [3-5] has shown that the simulated injection efficiency depends nearly as much on the model as it does on the injection site and depth of injection. Here our goal is to narrow the uncertainty range from the simulated efficiencies of these models, all of which followed the standard deep-injection scenario developed during the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP). We aim to do this by selecting models based on their skill in simulating radiocarbon and CFC-11, two key tracers of ocean circulation that have been measured with high precision throughout the world's oceans and that were simulated as part of OCMIP to evaluate modeled circulation [6,7]

METHODS

The eight modeling groups made simulations of deep-ocean CO2 sequestration according to the standard GOSAC-OCMIP protocols that were developed explicitly for this effort. In these protocols, we made two simplifications to conserve computing resources. First, model simulations neglected the influence of marine biota. Test simulations indicate that that this simplification changes results by less than 5% [8,3]. Second, model simulations carried only one type of tracer, total dissolved inorganic carbon (DIC). Thus we neglected potential changes in alkalinity induced by the interaction of injected CO2 with CaCO3 sediments. Such interaction can be neglected at least for several centuries after the start of injection [9].

For each injection simulation, we used ten separate DIC tracers: seven were used to track, individually, the seven DIC plumes extending from the seven injection sites; the three others were used to account for a control run, invasion of anthropogenic CO2, and a permanent sequestration scenario. Orr and Aumont [3] found that nonlinearities due to this multi-tracer approach were negligible, relative to a single-tracer approach. For instance atmospheric concentrations predicted by the multi-tracer vs. single-tracer approaches are nearly indistinguishable (maximum difference 0.15 ppmv). Injection was carried out simultaneously at the seven injection sites: Bay of Biscay (45.5°N, 4°W), New York (40°N, 68°W), Rio de Janeiro (24.4°S, 43°W), San Francisco (39°N, 126°W), Tokyo (36°N, 144°E), Jakarta (10°S, 109°E), and Bombay (19°N, 69°E). Modelers made separate 7-site simulations for each of three injection depths: 800 m, 1500 m, and 3000 m. Here we concentrate on the deepest injection.

With the standard OCMIP-2 formulation for gas exchange boundary conditions, models were first integrated to obtain preindustrial conditions, with atmospheric pCO2 held constant at 278 ppmv. Then, all models used the same predefined atmospheric CO2 record. Models followed observed atmospheric CO2 during the historical period, 1765--2000. Then, during 2000--2500, atmospheric CO2 followed IPCC future scenario S650, which eventually stabilizes atmospheric CO2 at 650 ppmv. Injection occurred only for 100 years, during 2000--2100, with 0.1 Pg C yr^{-1} being injected just offshore at each of seven injection sites. The full OCMIP-2/GOSAC simulation protocols are available at http://www.ipsl.jussieu.fr.

TABLE 1: GLOBAL INJECTION EFFICIENCY E_I (%) AND RELATED STATISTICS FOR THE 3000-M INJECTION SIMULATION

Model	*Year 2099*	*Year 2200*	*Year 2300*	*Year 2400*	*Year 2499*
AWI	97.2	84.7	71.2	58.9	48.6
CSIRO	97.6	91.9	83.9	74.5	65.1
IPSL(HOR)	99.0	97.7	93.8	88.6	83.1
IPSL(GM)	96.7	88.4	78.2	68.2	59.3
LLNL	99.6	96.5	90.2	83.1	76.2
MPIM	99.7	96.9	90.6	82.5	74.2
PIUB	99.9	97.9	92.3	84.5	76.2
PRINCE	100.0	99.7	98.4	95.9	92.7
PRINC2	99.9	98.4	93.9	87.2	80.0
SOC	97.3	85.2	72.6	62.1	53.4
Max – Min	3.3	15.0	27.2	37.0	44.1
Standard Deviation (σ)	1.3	5.7	9.5	12.2	13.9
Median	99.3	96.7	90.4	82.8	75.2
Mean	98.7	93.7	86.5	78.6	70.9
Weighted Mean (CFC-11)	98.3	92.0	83.9	75.5	67.7
Wt. Mean (Deep Pacific Natural ^{14}C)	99.0	94.5	87.6	80.0	72.6
Full Range	97 *to* 100	85 *to* 100	71 *to* 98	59 *to* 96	49 *to* 93
Mean Deep ^{14}C -Limited Range	—	92 *to* 98	84 *to* 94	74 *to* 89	65 *to* 83
CFC-11 Limited Range	—	85 *to* 98	73 *to* 91	62 *to* 84	53 *to* 76
CFC-11 & ^{14}C -Limited Range	—	92 *to* 98	84 *to* 91	74 *to* 84	65 *to* 76

RESULTS AND DISCUSSION

This model skill assessment carried out within OCMIP-2 is particularly relevant to the GOSAC injection activity. We found that among the 10 models, the global budgets for CFC-11 and C-14 are correlated with the global efficiency for the 3000-m injection simulation [5]. Here we exploit the effort in model skill assessment to help place realistic limits on range of behavior from the different models.

To illustrate the approach, let us start with the full range of simulated global injection efficiencies for the 3000-m injection. The injection efficiency E_i is simply the amount of injected CO2 that remains in the ocean divided by the total amount injected since the start of the simulation .In year 2500, i.e., 400 years after the end of a 100-year injection period, the range of injection efficiencies is from 49 to 93% (Table 1). Across the models, the 3000-m injection efficiency is correlated with the global mean for deep natural radiocarbon (R^2=0.57) (Figure 1). Generally then, the more negative is a model's natural ^{14}C, the older is the water, and the more efficient the model is in storing injected CO2. This correlation provides further impetus to use the skill assessment from the natural radiocarbon to provide narrower, more realistic limits for the global ocean 3000-m injection efficiency. We know that the observed global mean for deep-ocean natural radiocarbon (below 1500 m) is -172 permil based on the GLODAP synthesis [10] of the WOCE and JGOFS data. A conservative estimate of the associated uncertainty is ±25 permil. Five of the ten models (CSIRO, IPSL(HOR), LLNL, MPIM, PRINC2) fall within this range. Using only their efficiencies, we compute a "^{14}C-limited range" of 65 to 83% for the 3000-m injection efficiency at the end of the simulation. The same method is used to compute the efficiency range at other times throughout the 3000-m injection simulation. We did not apply the same technique to shallower injections (800 and 1500 m), where there was little or no correlation between injection efficiency and global mean, deep-ocean natural ^{14}C.

Surprisingly, we found an even a stronger correlation between the 3000-m injection efficiency and the global inventory of CFC-11 (R^2 = 0.81). Thus with an analogous approach to that taken for natural radiocarbon, we computed the "CFC-limited range" for the 3000-m injection efficiency at the end of the simulation (53 to 76%) as well as at other times. As for natural radiocarbon, we avoided applying the same technique to shallower injections, where there was little or no correlation between CFC-11 inventory and injection efficiency. The CFC-11 limited range overlaps the ^{14}C-limited range, but is slightly lower and wider.

Simultaneously accounting for constraints from both CFC-11 and natural radiocarbon further narrows the range for the 3000-m injection efficiency in year 2500. That is, the double-tracer constraint narrows the uncertainty, for the given 3000-m injection scenario in year 2500, by about a factor of four, from 71±22% to 70±6%. The uncertainty in the efficiency during previous years is likewise narrower, with a maximum range of about ±5% (Table 1).

In conclusion, we propose a basic ground rule for future studies of ocean injection efficiency: to be credible they must also demonstrate the associated model's skill in simulating the global inventory of CFC-11 and the global mean for radiocarbon in the deep ocean. A model that performs well in regards to both those constraints will be more likely to simulate reasonable global injection efficiencies. Nonetheless, efficiencies for a given injection site in coarse resolution models could be biased. For instance, the majority of injection sites will be located on eastern or western boundaries, which have known problems in coarse resolution models. Furthermore, coarse-resolution grids are unable to resolve important subgrid-scale processes (e.g., eddies, boundary currents, convection). Properly accounting for these processes may affect large-scale transport and could alter model predictions of CO_2 sequestration efficiency. Although, global-scale ocean general circulation models are now becoming available which do resolve these processes, their high resolution means that they can only be integrated for relatively short periods, a few decades at most. The challenge will be to develop innovative methods to make many long simulations of direct injection in these high-resolution ocean general circulation models. Continued developments in supercomputing, e.g., the Earth Simulator in Japan, may make it possible to make such a long high-resolution, injection simulation within a few years. New innovative approaches also need to be developed to accelerate such simulations.

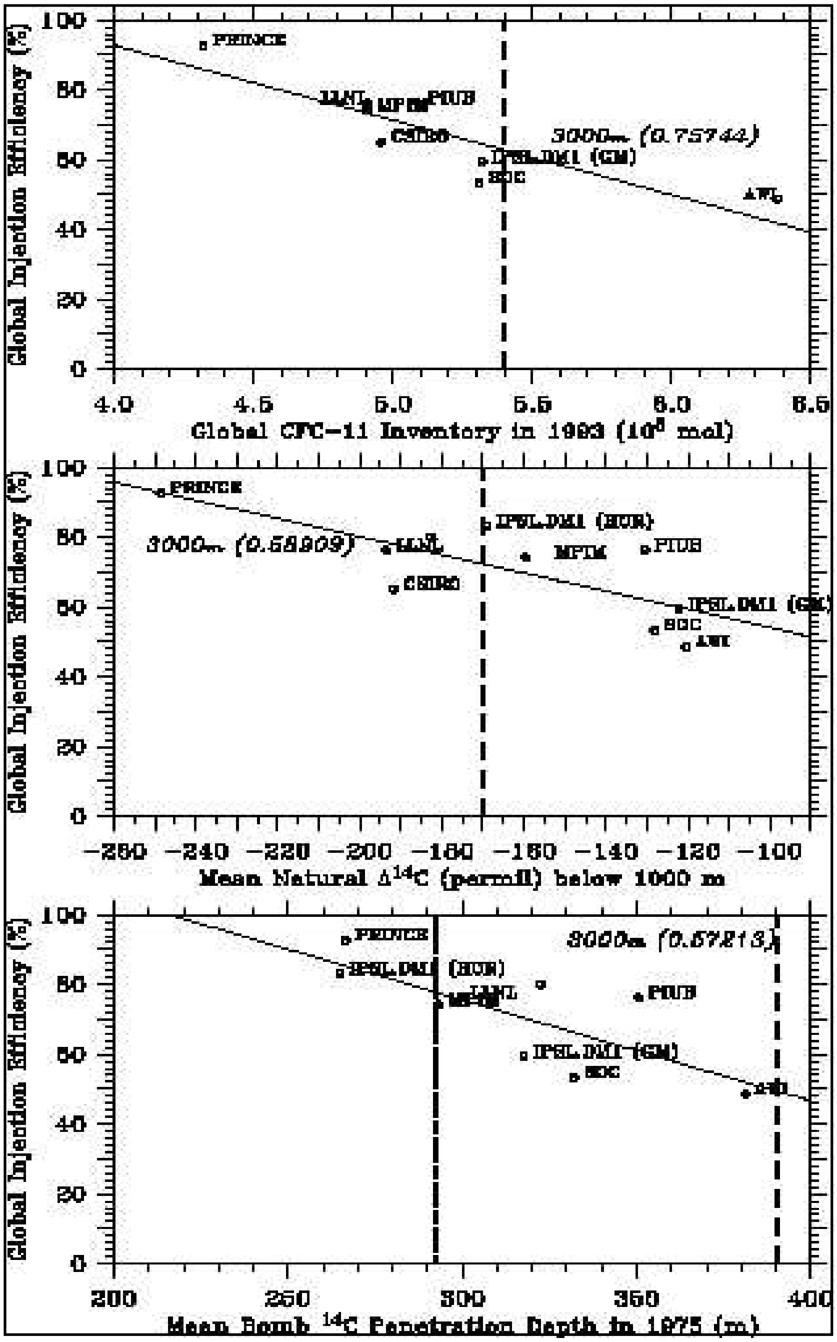

Figure 1: Comparison across the range of models of the simulated global injection efficiencies in year 2499 for injection at 3000 m with simulated CFC-11, natural ^{14}C, and bomb ^{14}C. The r^2 values are given in parentheses. The top panel shows the correlation for the 3000-m injection efficiency *Ei* vs. the global ocean inventory of CFC-11 [6]. The middle panel shows correlation of *Ei* with the global mean ^{14}C below 1000 m (weighted by volume). The bottom panel shows the correlation of *Ei* with the bomb ^{14}C penetration depth in 1975. Dashed lines indicate data-based estimates for the CFC-11 inventory (5.4×10^8 mol) [10], the mean deep-ocean ^{14}C (170 permil) [10], and for the mean bomb ^{14}C penetration depth (390 m) [11]. The dotted line (bottom panel only) is an alternative estimate of the bomb ^{14}C inventory [12] that is 25% lower. The most recent analysis also suggests an intermediate value [13]. but the uncertainties remain large and making the data-based estimates of bomb ^{14}C less useful than CFC-11 and natural ^{14}C for constraining injection efficiency.

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REFERENCES

1. Marchetti, C. 1977. On geoengineering and the CO_2 problem. *Climatic Change* 1, 59-68.
2. Hoffert, M.I., Y.-C. Wey, A.. J. Callegari, and W. S. Broecker 1979. Atmospheric response to deep-sea injections of fossil-fuel carbon

dioxide. *Climatic Change* 2, 53-68.

3. Orr, J.C. and Aumont O. 1999, Exploring the capacity of the ocean to retain artificially sequestered $CO_{2,}$ In: *Greenhouse Gas Control Technologies*, pp. 281-286, Eliasson BE, Reimer, P., and Wokaun A., Elsevier, Oxford.
4. Orr, J. C., O. Aumont, A. Yool, K. Plattner, F. Joos, E. Maier-Reimer, M.-F. Weirig, R. Schlitzer, K. Caldeira, M. Wickett, and R. Matear, 2001. Ocean CO2 sequestration efficiency from 3-D ocean model comparison, in *Greenhouse Gas Control Technologies, (Proceedings of the 5th Inter. Conf. on Green-house Gas Control Technologies)*, edited by D. Williams, B. Durie, P. McMullan, C. Paulson, and A. Smith, CSIRO, Collingwood, Australia, pp. 469-474.
5. Orr, J. C., O. Aumont, A. Yool, G.-K. Plattner, F. Joos, E. Maier-Reimer, M.-F. Weirig, R. Schlitzer, K. Caldeira, M. Wickett, R. Matear, B. Mignone, J. Sarmiento, J. Davison 2003. The GOSAC project to predict the efficiency of ocean CO_2 sequestration using 3-D ocean models, in *Greenhouse Gas Control Technologies--6th International Conference*, eds. J. Gale and Y. Kaya, Pergamon.
6. Dutay, J.-C., J.L. Bullister, S.C. Doney, J.C. Orr, R. Najjar, K. Caldeira, J.-M. Champin, H. Drange, M. Follows, Y. Gao, N. Gruber, M.W. Hecht, A. Ishida, F. Joos, K. Lindsay, G. Madec, E. Maier-Reimer, J.C. Marshall, R.J. Matear, P. Monfray, G.-K. Plattner, J. Sarmiento, R. Schlitzer, R. Slater, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool 2002.Evaluation of ocean model ventilation with CFC-11: comparison of 13 global ocean models. *Ocean Modelling, 4*, 89-120..
7. Matsumoto, K., J. L. Sarmiento, R. M. Key, O. Aumont, J. L. Bullister, K. Caldeira, J.-M. Campin, S. C. Doney, H. Drange, J.-C. Dutay, M. Follows, Y. Gao, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, K. Lindsay, E. Maier-Reimer, J. C. Marshall, R. J. Matear, P. Monfray, A. Mouchet, R. Najjar, G.-K. Plattner, R. Schlitzer, R. Slater, P. S. Swathi, I. J. Totterdell, M.-F. Weirig, Y. Yamanaka, A. Yool, and J. C. Orr 2004. Evaluation of ocean carbon cycle models with data-based metrics, *Geophys. Res. Lett.*, 31, L07303, doi:10.1029/2003GL018970, 2004.
8. Bacastow, R. B. and R. K. Dewey, Effectiveness of CO2 sequestration in the postindustrial ocean, *Energy Convers. Mgmt.*, *37*, 1079–1086, 1996.
9. Archer, D., H. S. Kheshgi, and E. Maier-Reimer 1998. Dynamics of fossil fuel CO2 neutralization by marine CaCO3. *Global Biogeochem. Cycles*, *12*, 259–276.
10. Key, R. M., C. L. Sabine, K. Lee and R. Wanninkhof, J.L. Bullister, R. A. Feely, F. J. Millero, C. Mordy, T.-H. Peng 2004. A global ocean carbon climatology: Results from GLODAP. *Global Biogeochem. Cycles* in press.
11. Broecker, W. S., S. Sutherland, W. Smethie, T.-H. Peng, and G. Ostlund 1995. Oceanic radiocarbon: separation of the natural and bomb components. *Global Biogeochem. Cycles 9*, 263–288.
12. Hesshaimer, V., M. Heimann, and I. Levin 1994. Radiocarbon evidence for a smaller oceanic carbon dioxide sink than previously believed. *Nature*, *370*, 201–203.
13. Peacock, S. 2004. Debate over the ocean bomb radiocarbon sink: Closing the gap. *Global Biogeochem. Cycles* 18, GB2022, doi:10.1029/2003GB002211.