GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 5, NO. 4, PAGES 309-313, DECEMBER 1991

OCEANIC UPTAKE OF ANTHROPOGENIC CO_2: THE MAJOR UNCERTAINTIES

J. L. Sarmiento

Program in Atmospheric and Oceanic Sciences
Princeton University, Princeton, New Jersey

INTRODUCTION

The recent notes by Broecker [1991] and by Smith and Mackenzie [1991] rightfully point out that many oceanographers do not have a clear grasp of the relationship between the oceanic biological pump and anthropogenic CO_2 transient. This misunderstanding has unfortunately led some scientists to make misleading claims as to the importance of the biological pump in the anthropogenic transient. It is remarkable that someone who contributed as much to our understanding of the oceanic carbon cycle as Revelle could have incorrectly stated that the biological pump takes up anthropogenic CO_2 [Revelle, 1990]. However, both notes go too far when they dismiss the biological pump as being of minimal relevance to global change, with a particular indictment by Broecker of the Joint Global Ocean Flux Study (JGOFS) as having been guilty of "tarnishing the integrity of global change research" by "hitching their wagons to the greenhouse star." The following brief overview of issues that are important in estimating oceanic uptake of anthropogenic CO_2, and where the biological pump fits into them, is offered as an attempt to strike a more balanced point of view. Sarmiento and Siegenthaler [1991] give a more detailed discussion.

THE BIOLOGICAL PUMP

Broecker qualifies his downgrading of the importance of the biological pump in global change by stating that his assessment applies if one ignores (1) the potential for increased biological stripping of nutrients from the surface ocean if thermocline and deep ocean ventilation are slowed as a consequence of global warming, and (2) the iron fertilization scenario. In fact, one of the greatest uncertainties we have in predicting future oceanic uptake of anthropogenic CO_2 is how this will be affected by the modifications in ocean circulation and biology that will almost certainly occur with climate warming. I agree with Broecker that the most important effect of ocean circulation changes such as those found by the greenhouse warming simulations of Manabe et al. [1991] will be on the direct passive uptake of CO_2 by gas exchange, dissolution, and transport. For this we need better ocean circulation and coupled air-sea models. However, the biological pump will also be affected in ways that we do not yet clearly understand.

An important clue as to the potential impact of changes in the biological pump comes from the remarkable observation from trapped air bubbles in ice cores that atmospheric pCO_2 was of the order of 80 to 100 ppm lower during the last ice age [e.g., Neftel et al., 1982; Barnola et al., 1987]. Additional constraints on this phenomenon come from the ocean sedimentary record. We do not have the final answer as to how this CO_2 reduction occurred, but most of the postulated mechanisms involve the biological pump. Smith and Mackenzie erroneously point to one of my papers [Sarmiento et al., 1990] as having said something similar to Revelle [1990] as to the relationship between anthropogenic CO_2 and the biological pump. In fact, my paper was referring to one of the mechanisms which has received considerable attention as an explanation for the ice age pCO_2 reduction: removal of nutrients from the vast areas of the southern ocean that have very high surface nutrients at the present time [e.g., Knox and McElroy 1984; Siegenthaler and Wenk 1984; and Sarmiento and Toggweiler 1984]. Such a removal might have occurred either by increased export of organic matter or by reduced upward supply of nutrients.

Reduction of the high nutrients in the southern ocean can give atmospheric CO_2 uptakes of as much as 1 to 2 GT C/yr

Paper number 91GB02705.
0886-6236/91/91GB-02705$02.00

over time scales of a century [e.g., Peng and Broecker 1991; Joos et al., 1991]. Upper limit scenarios of the effect of a total depletion of southern ocean nutrients on atmospheric pCO_2 give a reduction of the order of 20% in the 100 year high emission "business as usual" anthropogenic emissions scenario of the IPCC [Houghton et al., 1990] over what the atmospheric pCO_2 would be in the absence of nutrient depletion, and as much as 50% in a low emission scenario with total anthropogenic emissions fixed at their 1990 value [Sarmiento and Orr, 1991]. While such extreme scenarios of nutrient depletion are highly unlikely, it is imprudent to argue that an improved grasp of southern ocean carbon cycling dynamics is of minimal relevance to global change. Furthermore, such an understanding is essential if we are to provide wise counsel to those who might wish to push for mitigation strategies such as the southern ocean iron fertilization scenario. JGOFS is developing plans for both a southern ocean process study and iron fertilization experiment. Surely these must be considered as highly relevant to global change.

Smith and Mackenzie incorrectly assert that the only way the oceanic biological pump can play a direct role in taking up anthropogenic CO_2 is if a fresh supply of land-derived nutrients is added to the ocean. While it is true that land-derived nutrients will increase CO_2 uptake (if the addition occurs in a nutrient limited region of the ocean), the potential impact of this process is quite small. Sabine and Mackenzie [1991] estimate that direct uptake of carbon by consumption of excess nutrients being added to the oceans by rivers at the present is of order 0.3 GT C/yr. However, the chemical buffering effect of the oceanic carbon system results in only ~17% of this CO_2 coming from the atmosphere [e.g., Maier-Reimer and Hasselmann 1987; Sarmiento et al., 1991]. The equilibrium effect of riverine excess nutrients on atmospheric pCO_2 will thus be a relatively insignificant ~0.05 GT C/yr. The southern ocean nutrient depletion scenario, which was ignored in Smith and Mackenzie's note, has a potential impact more than an order of magnitude larger than this.

THE SOLUBILITY PUMP

Smith and Mackenzie also state that a change in the supply of nutrients to the surface by vertical circulation will not affect atmospheric CO_2. In the nutrient-limited regions of the ocean, which occur primarily in low latitudes, an increased supply of nutrients by upwelling would amplify biological uptake, which would strip out the additional nutrients being added to the surface and reduce carbon according to the Redfield ratio. To the extent that the nutrients and biologically utilized carbon are locked into the Redfield relationship during production and regeneration of organic matter, Smith and Mackenzie are correct in their assertion that the carbon thus removed would be equivalent to the excess carbon in the deep waters brought to the surface, and that the average surface carbon content would remain unaltered by a change in upwelling.

However, the evidence for a constant Redfield ratio in regeneration of organic matter is weak at best, a problem the JGOFS process studies should provide help with. In addition, even if the constant Redfield ratio assumption is correct and we leave out the southern ocean biological pump mechanism already discussed above, the nutrient and carbon budgets are not exactly in balance with each other because of the effect of temperature on CO_2 solubility. The low-latitude upwelling areas of the ocean have excess CO_2 due in part to the warming of the cold waters being brought to the surface (e.g., the equator); these areas of CO_2 loss to the atmosphere are compensated by areas of CO_2 gain in high latitudes where cooling of surface waters leads to CO_2 deficits relative to the atmosphere (e.g., the North Atlantic [cf. Keeling, 1968; Tans et al., 1990]). This "solubility pump" [Volk and Hoffert, 1985] would increase atmospheric pCO_2 with augmented low- latitude upwelling, because such upwelling would bolster the influence of low-latitude high pCO_2 waters in the overall atmospheric CO_2 balance [e.g., Sarmiento and Toggweiler, 1984]. Reduced upwelling (a more likely scenario in the case of global warming) would reduce atmospheric pCO_2. The magnitude of these effects has not been adequately explored as yet.

CARBON SYSTEM MEASUREMENTS

Broecker's critique of the JGOFS program in the context of a discussion of the biological pump fails to recognize that JGOFS is not confined to biological process studies alone. Other major components of the JGOFS program are the Department of Energy funded carbon system measurements that are being carried out on World Ocean Circulation Experiment (WOCE) cruises, as well as extensive carbon system measurements being carried out on JGOFS cruises and the time series stations at Bermuda and Hawaii. Such monitoring is essential if we are to obtain direct corroboration of model assessments of oceanic anthropogenic CO_2 uptake and improve our understanding of how this carbon enters the ocean.

One way of monitoring the oceanic invasion of CO_2 is by estimating the air-sea flux directly. This requires not only accurate air-sea pCO_2 difference measurements, but also a measure of the gas exchange coefficient. There continues to be considerable uncertainty as to the magnitude of the gas exchange coefficient in the ocean [e.g., Watson et al., 1991b] which has not yet been adequately addressed. However, the primary reason that many oceanographers have not previously been optimistic about estimating air-sea fluxes directly is that the total oceanic uptake of anthropogenic CO_2 (~2 GT C/yr) requires a very small globally averaged air-sea CO_2 difference of only 8 ppm. It is extremely difficult to make air-sea CO_2 measurements with the accuracy of order a few ppm that would be required to resolve this number. Two recent developments show promise for improving this situation. One is a result of atmospheric transport model studies such as those of Tans et al. [1990] and Keeling et al. [1989] which place strong constraints on the geographic distribution of oceanic CO_2 uptake. The Tans et al. and Keeling et al. estimates of total oceanic uptake differ by approximately a factor of 4, with disparities of the order of 10 to 20 ppm in the air-sea CO_2 differences they require over regions of the ocean such as the southern ocean, North Atlantic, and North Pacific. The measurement accuracy required to differentiate between these scenarios should be readily attainable. The second development may help with the problem of time variability in the air-sea CO_2 difference resulting from seasonal changes in temperature and biological processes. The strong correlation that Watson et al., [1991a] found between chlorophyll and pCO_2 in the JGOFS North

Atlantic Bloom Experiment suggests the possibility of using satellite based estimates of chlorophyll, coupled with satellite-based temperature and gas exchange coefficient estimates, to aid in monitoring the oceanic pCO_2. Such an approach will work only with extensive ground validation studies. This is a valuable contribution that can be made by JGOFS process studies in various regions of the ocean such as the North Atlantic, and upcoming studies in the Equatorial Pacific and Indian Ocean.

The recent Tans et al. [1990] study gives an excellent illustration of the value of air-sea flux estimates, and their potential for teaching us important new things about how the oceans take up anthropogenic CO_2. Tans et al. made use of atmospheric models and observations, combined with air-sea fluxes obtained from measurements of the air-sea CO_2 difference, to obtain an estimated air-sea CO_2 flux of 0.3 to 0.8 GT C/yr, very much smaller than estimates of 1.7 to 2.8 GT C/yr obtained from ocean circulation models [e.g., Houghton et al., 1990; Sarmiento et al., 1991]. A resolution to most of the inconsistency raised by the Tans et al. study may be that there was a large pre-anthropogenic outward CO_2 flux required to balance the net river inflow [e.g., Sabine and Mackenzie, 1991]. It appears that this flux must be incorporated in the total anthropogenic CO_2 budget [Sarmiento and Siegenthaler, 1991; J. L. Sarmiento and E. Sundquist, Oceanic uptake of anthropogenic CO_2: a new budget, submitted to *Nature*, 1991].

Another way of monitoring the oceanic invasion of anthropogenic CO_2 directly is by measuring the increase in oceanic total carbon content with time. The invasion of anthropogenic CO_2 is increasing surface total carbon concentrations by the order of 1/2 to 1 μmol/kg per year. Present measurement precisions are of the order of 1.5 μmol/kg or better; although interlaboratory differences of as much as 10 to 20 μmol/kg were found in a recent intercalibration exercise [UNESCO, 1991], suggesting that accuracy is still a serious problem. Work which is presently underway should greatly improve the accuracy to the point where one can expect to obtain reasonable estimates of changes in total carbon standing crop by making measurements separated by 1 or 2 decades.

There has also been an interest in using total carbon measurements made at one point in time to estimate the increase in standing crop due to the anthropogenic invasion [Brewer, 1978; Chen and Millero, 1979]. This requires a correction of the total carbon concentration for organic carbon regeneration and $CaCO_3$ dissolution, for which one can use apparent oxygen utilization estimates and alkalinity measurements. The accuracy of this technique is very low because of the difficulty of making these corrections. It is thus unlikely that it will be of use for more than providing a qualitative view of anthropogenic CO_2 uptake. More promising is the possibility of using total carbon measurements to estimate transport of carbon across various sections of the ocean [e.g., Brewer et al., 1989]. One of the most important recent advances in our understanding of the carbon cycle is the use of atmospheric transport models and observations to constrain the geographic distribution of the air-sea CO_2 flux [e.g., Tans et al., 1990]. These models imply a large southward transport of carbon from the northern to southern hemisphere [Sarmiento et al., 1991] which one should be able to estimate directly using inverse modeling techniques such as those of Rintoul and Wunsch [1991].

OCEAN CIRCULATION

The most important and reliable information we have regarding oceanic uptake of anthropogenic CO_2 in the past and present comes from estimates using ocean circulation models. The key aspect of these models that gives us confidence is their calibration or validation with bomb produced radiocarbon estimates based on GEOSECS observations, and, to a lesser extent, estimates of the natural bomb carbon distribution based on the same data set. Tracers are essential because none of the models gives an accurate representation of oceanic transport processes. Two other sets of tracers have the global scope and relatively simple boundary conditions that make radiocarbon so powerful: chlorofluorocarbons and argon 39. However, their use has been limited to date because we lack a global set of measurements.

The World Ocean Circulation Experiment is well on the way to providing global coverage of chlorofluorocarbon measurements. WOCE is also obtaining an extensive number of small volume water samples for accelerator mass spectrometry (AMS) measurements of radiocarbon at the new Woods Hole facility. However, it is disconcerting that an exclusive commitment has been made to the AMS approach without the Woods Hole facility having made its first measurement. In addition, the AMS procedure is a factor of 2 to 5 less precise than large volume beta counted measurements [Sarmiento, 1988], a difference which is important in the deep ocean. We need a balanced tracer measurement program which includes a modest number of large volume radiocarbon measurements concentrated in the deep ocean, as well as measurements that can be used to calibrate the old beta techniques with the new AMS technique.

Estimating the oceanic uptake of anthropogenic CO_2 in the future requires development of coupled air-sea models, a subject already mentioned in the section on the biological pump.

CONCLUSION

In conclusion, I would return to what I see as the central theme of Broecker's editorial, with which I agree: that it is important for scientists to always have in mind that the work of pinning down the budget for anthropogenic CO_2 does not occur in a vacuum, no more than any of the other important global warming issues. Almost all industrial countries of the world have already adopted measures to control CO_2 emissions in direct response to concerns about global climate change [Schmidt, 1991]. The next decade will very likely see the forging of global protocols for anthropogenic CO_2 emissions aimed at attaining specific targets for future atmospheric CO_2 levels. This will greatly increase the pressure on the scientific community to provide predictions of CO_2 levels for various emissions scenarios, as well as assistance in evaluating scenarios for mitigating that increase. It is this specter that we must have in mind as we advise government agencies on how to channel global change carbon cycle research funding, funding for which they have every right to expect meaningful results.

On the other hand, it would be unwise for us to prematurely jump to conclusions that aspects of the carbon cycle which we poorly understand at present are irrelevant. A narrowly focused research program will very likely miss important things that may be of considerable importance. Perhaps we can draw a

lesson from two experiences of the last decade which have completely reshaped our thinking of the carbon cycle. Prior to the discovery of reduced atmospheric pCO_2 levels during the last ice age, most geochemists were convinced that changes such as these could not occur. In fact, my own early views on the stability of atmospheric pCO_2 were developed under very strong influence from Broecker. Now we have a long catalog of possible mechanisms, though no final choice or set of choices which fits all the observational constraints. A second lesson comes from the Tans et al. [1990] study discussed above. It forced us to look hard at just how the carbon cycle works and to realize that there were important aspects of it that we had previously ignored. Are there other surprises awaiting us? Is our understanding of what controls siliceous versus calcareous production adequate to dismiss the possibility of significant climate induced shifts? Might the large oceanic dissolved organic carbon reservoir of the order of 1600 GT C (Pelzer et al., personal communication) change in response to changes in ocean temperature or ecology? We have very little idea how to answer questions such as these at the present time.

Acknowledgments. Comments by H. Ducklow, J. Mahlman, S. Manabe, R. Murnane, U. Siegenthaler, and R. Toggweiler, as well as the assistance of J. Olszewski, are gratefully acknowledged. My carbon cycle research is funded by the Carbon Dioxide Research Division, U.S. Department of Energy (DE FG02-90ER61052) and by the National Science Foundation (OCE-9012333).

REFERENCES

Barnola, J. M., D. Raynaud, Y. S. Korotkevitch, and C. Lorius, Vostok ice core: A 160,000 year record of atmospheric CO_2, *Nature, 329*, 408-414, 1987.

Brewer, P. G., Direct observation of the oceanic CO_2 increase, *Geophys. Res. Lett., 5*, 997-1000, 1978.

Brewer, P. G., C. Goyet, and D. Dyrssen, Carbon dioxide transport by ocean currents at 25° N latitude in the Atlantic Ocean, *Science, 246*, 477-479, 1989.

Broecker, W. S., Keeping global change honest, *Global Biogeochem. Cycles, 5*, 191-192, 1991.

Chen, C.-T., and F. J. Millero, Gradual increase of oceanic CO_2, *Nature, 277*, 205-206, 1979.

Houghton, J.T., G. T. Jenkins, and J.J. Ephraums, *Climate Change, the IPCC Scientific Assessment*, Cambridge U. Press, Cambridge 1990.

Joos, F., J. L. Sarmiento, and U. Siegenthaler, Estimates of the effect of southern ocean iron fertilization on atmospheric CO_2 concentrations, *Nature, 349*, 772-775, 1991.

Keeling, C. D., Carbon dioxide in surface ocean waters, 4, Global distribution, *J. Geophys. Res., 73*, 4543-4553, 1968.

Keeling, C. D., S. C. Piper, and M. Heimann, A three dimensional model of atmospheric CO_2 transport based on observed winds, 4, Mean annual gradients and interannual variations, in *Aspects of Climate Variability in the Pacific and the Western Americas, Geophys. Monogr. Ser.*, vol. 55, edited by D. H. Peterson, pp. 305-363, AGU, Washington, D.C., 1989.

Knox, F., and M. McElroy, Changes in atmospheric CO_2 : Influence of the marine biota at high latitudes, *J. Geophys. Res., 89*, 4629-4637, 1984.

Maier-Reimer, E., and K. Hasselmann, Transport and storage of CO_2 in the ocean — An inorganic ocean-circulation cycle model, *Clim. Dyn., 2*, 63-90, 1987.

Manabe, S., R. J. Stouffer, M. J. Spelman and K. Bryan, Transient responses of a coupled ocean-atmosphere model to gradual changes, *J. of Clim., 4*, 785-818, 1991.

Neftel, A., H. Oeschger, J. Schwander, B. Stauffer, and R. Zumbrunn, Ice core sample measurements give atmospheric CO_2 content during the past 40,000 years, *Nature, 295*, 220-223, 1982.

Peng, T.-H., and W. S. Broecker, Dynamic limitations on the Antarctic iron fertilization strategy, *Nature, 349*, 227-229, 1991.

Revelle, R., Letter in Forum Section, *Issues Sci. Technol., 7* (2), 21-22, 1990.

Rintoul, S., and C. Wunsch, Mass, heat, oxygen and nutrient fluxes and budgets in the North Atlantic Ocean, *Deep Sea Res., 38*, suppl., S355-S377, 1991.

Sabine, C. L., and F. T. Mackenzie, Oceanic sinks for anthropogenic CO_2, *Int. J. Energy Environ. Econ. 1*, 119-127, 1991.

Sarmiento, J. L., A chemical tracer strategy for WOCE: Report of a workshop held in Seattle, Washington, January 22 and 23, 1987, *Rep. 10*, U. S. Plann. Off. for WOCE, College Station, Tex., 1988.

Sarmiento, J. L., and J. C. Orr, Three dimensional ocean model simulations of the impact of southern ocean nutrient depletion on atmospheric CO_2 and ocean chemistry, *Limnol. Oceanogr.*, in press, 1991.

Sarmiento, J. L., and U. Siegenthaler, New production and the global carbon cycle, in *New Production and the Global Carbon Cycle*, edited by P. Falkowski and A. Woodhead, Plenum, New York, in press, 1991.

Sarmiento, J. L., and J. R. Toggweiler, A new model for the role of the oceans in determining atmospheric pCO_2, *Nature, 308*, 621-624, 1984.

Sarmiento, J. L., G. Thiele, R. M. Key, and W. S. Moore, Oxygen and nitrate new production and remineralization in the North Atlantic subtropical gyre, *J. Geophys. Res., 95*, 18,303-18,315, 1990.

Sarmiento, J. L., J. C. Orr, and U. Siegenthaler, A perturbation simulation of CO_2 uptake in an ocean general circulation model, *J. Geophys. Res.*, in press, 1991.

Schmidt, K., Industrial countries' responses to global climate change, Spec. Rep., Environ. and Energy Study Inst., Washington, D. C., 1991.

Siegenthaler, U., and T. Wenk, Rapid atmospheric CO_2 variations and ocean circulation, *Nature, 308*, 624-625, 1984.

Smith, S. V., and F. T. Mackenzie, Comments on the role of oceanic biota as a sink for anthropogenic CO_2 emissions, *Global Biogeochem. Cycles, 5*, 189-190, 1991.

Tans, P. P., I. Y. Fung, and T. Takahashi, Observational constraints on the global atmospheric CO_2 budget, *Science, 247*, 1431-1438, 1990.

UNESCO, Report of second session of the Joint JGOFS-CCCO Panel of Carbon Dioxide, Paris, 1991.

Volk, T., and M. I. Hoffert, Ocean carbon pumps: Analysis of

relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes, in *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present, Geophys. Monogr. ser.*, vol. 32, edited by E. Sundquist and W. S. Broecker, pp. 99-110, AGU, Washington, D.C., 1985.

Watson, A. J., C. Robinson, J. E. Robinson, P. J. le B. Williams, and M. J. R. Fasham, Spatial variability in the sink for atmospheric carbon dioxide in the North Atlantic, *Nature, 350*, 50-53, 1991a.

Watson, A. J., R. C. Upstill-Goddard, and P. S. Liss, Air-sea gas exchange in rough and stormy seas measured by a dual-tracer technique, *Nature, 349*, 145-147, 1991b.

J.L. Sarmiento, Program in Atmospheric and Oceanic Sciences, P.O. Box CN710, Princeton University, Princeton, NJ 08544-0710.

(Received October 3, 1991;
accepted October 25, 1991.)