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Annual Report

"SIMULATIONS OF THE GLOBAL CARBON CYCLE AND
ANTHROPOGENIC CO₂ TRANSIENT"I. Year 1 Accomplishments

The major aims of our research are: (1) to improve our understanding of the anthropogenic transient using observations and models of the past and present, and (2) to develop an ability to predict the future of the carbon cycle in response to continued anthropogenic perturbations and climate change. During the first year of the present grant we published 10 papers and completed an additional 3 papers that are either in press or in an advanced state of preparation. We discuss the results of this research in the following two sub-sections.

Year 1 Publications

- [1] Anderson, L. A., and J. L. Sarmiento, 1994. Redfield ratios of remineralization determined by nutrient data analysis. *Global Biogeochem. Cycles*, 8: 65-80.
- [2] Fasham, M. J. R., J. L. Sarmiento, R. D. Slater, H. Ducklow, and R. Williams, 1993. Ecosystem Behavior at Bermuda Station "S" and OWS "India": a GCM model and observational analysis. *Global Biogeochem. Cycles*, 7: 379-416.
- [3] Murnane, R. J., 1994. Determination of thorium and particle cycling rate constants at Station P: a comparison of least squares techniques. *J. Geophys. Res.*, 99: 3393-3405.
- [4] Murnane, R. J., J. K. Cochran, and J. L. Sarmiento, 1994. Estimates of particle- and thorium-cycling rates in the northwest Atlantic Ocean. *J. Geophys. Res.*, 99: 3373-3392.
- [5] Sarmiento, J. L., 1993. Ocean carbon cycle. *Chemical and Engineering News*, 71: 30-43..
- [6] Sarmiento, J. L., 1993. Atmospheric CO₂ stalled. *Nature*, 365: 697-698.
- [7] Sarmiento, J. L., and M. Bender, 1994. Carbon biogeochemistry and climate change. *Photosynthesis Res.*, 39: 209-234.
- [8] Sarmiento, J. L., R. D. Slater, M. J. R. Fasham, H. W. Ducklow, J. R. Toggweiler, and G. T. Evans, 1993. A seasonal three-dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone. *Global Biogeochem. Cycles*, 7: 417-450.
- [9] Siegenthaler, U., and J. L. Sarmiento, 1993. Atmospheric carbon dioxide and the ocean. *Nature*, 365: 119-125.

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- [10] Slater, R. D., J. L. Sarmiento, and M. J. R. Fasham, 1993 Some parametric and structural simulations with a three dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone. In: Towards a Model of Biogeochemical Ocean Process, edited by G. Evans and M. Fasham, NATO ASI Series 1, Global Environmental Change, Vol. 10, Springer-Verlag, Berlin, pp. 291-294.

In press and in preparation:

- [11] Sarmiento, J. L., C. Le Quéré, and S. W. Pacala, in press. Limiting future atmospheric carbon dioxide. (Global Biogeochem. Cycles)
- [12] Sarmiento, J. L., and P. Rayner, R. Murnane, and C. Le Quéré, in preparation. Constraints on the spatial distribution of carbon sources and sinks.
- [13] Sarmiento, J. L., and S. Pacala, in preparation. Terrestrial uptake of anthropogenic carbon.

A.- Understanding the Anthropogenic Carbon Budget

We have been studying three aspects of the anthropogenic carbon budget: (1) the globally integrated budget at the present time, (2) the time history of the carbon budget, and (3) the spatial distribution of carbon fluxes. Our understanding of the globally integrated budget continues to be limited by our inability to demonstrate the existence of the terrestrial sink that has been proposed to account for the "missing sink" (reference [9]) We have used our ocean models in combination with atmospheric observations and other constraints on the carbon budget in order to estimate a time history of the missing sink (reference [13]). We fit the missing sink time history with a new terrestrial model. The results of this fit are consistent with CO₂ fertilization as the major mechanism for terrestrial uptake, but the uncertainties are very large.

Perhaps the most promising development in our research has been a new study of the spatial distribution of carbon sources and sinks using a new atmospheric GCM model simulation in combination with a new simulation of the ocean carbon cycle (reference [12]). The results of this work demonstrate that we have a very poor understanding of the oceanic source and sink distribution. They also suggest an overall terrestrial sink distribution consistent with CO₂ fertilization as the main mechanism for this sink. Our largest imbalances occur in the tropics, where we have too large a source, and in the southern hemisphere, where we have too large a sink. The tropical imbalance can be redressed if the deforestation estimate of 1.6 Pg C/yr is reduced. The southern hemisphere sink can be reduced by modifying the air-sea flux in this region, as previously suggested by Keeling, et al. [1989b]. Possible mechanisms may be a larger thermohaline overturning than predicted by our ocean model, combined with

the impact of the degassing flux required to balance the river inflow of bicarbonate from weathering.

Our research in each of these areas is discussed in more detail the following three sub-sections.

(1) Globally integrated budget

Our most important paper on the globally integrated anthropogenic carbon budget is [9]. This paper summarizes our view of the present understanding of the oceanic sink for anthropogenic carbon dioxide, including past work by our group. Simulating the oceanic uptake of anthropogenic CO₂ requires models of ocean chemistry and circulation. The chemistry of carbon, which determines the total oceanic capacity for CO₂, is well understood. Ocean circulation determines the rate at which the oceanic CO₂ chemical uptake capacity is utilized. Model simulations show that the rate of gas exchange exerts only a modest control (e.g., Sarmiento, et al. [1992]). The exchange between the surface mixed layer and the interior is estimated using ocean models such as those in the following table from [9].

Table 1. Oceanic Uptake of Anthropogenic CO₂

Model	Reference	Present Ocean Uptake (Pg C/yr)
Box-diffusion	Siegenthaler [1983]	2.3
HILDA	Siegenthaler and Joos [1992]	2.1
Princeton GCM	Sarmiento, et al. [1992]	1.9
Hamburg GCM	Heimann & Maier-Reimer (pers. comm.)	1.6
Best Estimate		2.0±0.6

These models all give similar estimates of oceanic uptake of anthropogenic CO₂ for the present time. Direct observational confirmation of the oceanic uptake has proved extremely difficulty to obtain. Because of this, and the fact that all the ocean circulation models have problems, the primary reason we have confidence in the model estimates is because we are able to calibrate the ocean models with bomb radiocarbon estimates obtained from GEOSECS observations. The uncertainty in the "best estimate" is based on the range in the model results and includes a ±20% error in the bomb radiocarbon inventory.

Combining these oceanic uptake estimates with other estimates of the anthropogenic carbon fluxes gives the following overall budget taken from [9] as modified by [12]:

Table 2. Global Atmospheric Carbon Budget for 1985

	Flux Term	Pg C/yr
F^{ocean}	$F^{\text{ocean}}_{\text{pre-industrial}}$	0.0
	$F^{\text{ocean}}_{\text{degassing}}$	0.6 ± 0.2
	$F^{\text{ocean}}_{\text{uptake}}$	-2.0 ± 0.6
	Total Sea-Air Flux	-1.4 ± 0.6
$F^{\text{terrestrial}}$	$F^{\text{terrestrial}}_{\text{weathering}}$	-0.6 ± 0.2
	$F^{\text{terrestrial}}_{\text{CO}_2 \text{ fertilization}} + F^{\text{terrestrial}}_{\text{N fertilization}} + F^{\text{terrestrial}}_{\text{climate}}$	-1.7 ± 1.3
	$F^{\text{terrestrial}}_{\text{landuse}}$	1.6 ± 1.3
	Total Land-Air Flux	-0.7 ± 0.8
F^{fossil}		5.2 ± 0.5
$F^{\text{atmosphere}}$	Atmospheric Increase	3.1 ± 0.2

The terrestrial weathering and ocean degassing terms are part of the weathering cycle that includes a flux of 0.6 Pg C/yr from the land to the ocean via rivers (Sarmiento and Sundquist [1992]). The total oceanic uptake is thus 2.0 Pg C/yr, but the sea-air flux is only 1.4 Pg C/yr. The uncertainty in the weathering and degassing terms is based on the range of results given in the literature. The true uncertainty is almost certainly much larger.

The terrestrial uptake term of 1.7 Pg C/yr, with an uncertainty of 1.3, is estimated by taking the difference of all other sources and sinks and assuming that this residual is due to terrestrial processes. Aside from the land use term, which we obtain from Houghton, et al. [1990], terrestrial uptake is the most weakly constrained of the budget terms. Because of the large magnitude of this sink, and its high uncertainty, we have begun to dedicate a considerable amount of effort to improving our understanding of terrestrial processes. The major focus our research has been on the time history of terrestrial uptake as described in the following section.

(2) Temporal history

The temporal evolution of the carbon budget provides important constraints on that budget. Figure 1 shows results from our recent study of the time history of the carbon budget (reference [13]). Measurements of CO₂ in air bubbles trapped in ice cores, combined with modern observations, now cover the entire industrial era (Neftel, et al. [1982]; Friedli, et al. [1986]; Siegenthaler, et al. [1988]; Wahlen, et al. [1991]; and Keeling and Whorf [1991]). Estimates of oceanic uptake have been obtained by forcing ocean models with the atmospheric observations using the model of Sarmiento, et al. [1992]. Fossil fuel production

estimates are available from 1800 onwards (Marland, et al. [1989]), and land use estimates go back to 1850 (Houghton [1992]). Combining these sources and sinks (Figure 1a) gives the missing sink estimate of Figure 1b. Our new time series shows large interannual variability (up to 3 Pg/yr) about an average of approximately 2 Pg/yr. The magnitude of the missing sink has a very large uncertainty due primarily to uncertainty in the land use source. It is generally assumed that the missing sink is due to uptake by the terrestrial biosphere.

Figure 1. (a) Upper panel shows the time history of "known" carbon sources and sinks. (b) Lower panel shows the "missing sink" estimated from the curves in (a). The dashed line is a model fit of a simple terrestrial model forced with the observed atmospheric CO₂ content and temperature (reference [13]).

Three mechanisms that have been proposed to explain the terrestrial sink are enhanced growth due to increased CO₂ concentration, fertilization by nitrogen added to the land in fertilizers and oxides released by fossil fuel

burning, and the response of the terrestrial biosphere to climate. Increased plant growth response to increased CO₂ has been demonstrated in numerous experimental studies (e.g., summary by Dahlman [1993]). Many terrestrial ecosystems are nitrogen limited and will respond to added nitrogen with enhanced growth (e.g., Vitousek and Howarth [1991]; and Schindler and Bayley [1993]). The response of plants to long term climate change has been addressed in numerous studies (e.g., Smith, et al. [1992]; and Melillo, et al. [1993]). Dai and Fung [1993] have shown that the response to climate changes over the last few decades may have been quite large. The existence of CO₂ and nitrogen fertilization in nature, the relative contributions of these two mechanisms to the total terrestrial uptake, the interaction between CO₂ and nitrogen limitation (e.g., Comins and McMurtrie [1993]), and the climate impact on terrestrial biota, are all speculative and highly controversial. With few exceptions (e.g., Wofsy, et al. [1993]), there is no hard evidence to establish whether the terrestrial sink even exists. Tree ring measurements (e.g., Auclair and Androsko [1993] and D'Arrigo and Jacoby [1993]) are controversial and ambiguous.

We fit a simple model of the terrestrial biosphere to the time series of Figure 1b, allowing for forcing by CO₂ fertilization through a Michaelis-Menten term, as well as forcing by temperature through its influence on photosynthesis and decay (the latter is dominant). The fitted model accounts well for the long term pattern and interannual variability, providing an estimate of 0.36 for the increase in net primary productivity resulting from a doubling of CO₂ (β), and an estimate of 2.4 for the increase in respiration and decay resulting from a 10° increase in temperature (Q_{10}). The long term pattern is driven primarily by CO₂, whereas the interannual variability is primarily due to the temperature forcing. These estimates of the terrestrial biosphere's response to CO₂ and temperature are virtually identical to independent measurements obtained in small-scale field and laboratory studies. This lends support to the idea that the sink is due to CO₂ fertilization, although the uncertainties are very large.

(3) Spatial distribution

The spatial distribution of sources and sinks provides an important constraint on the carbon budget because of the requirement that the local budget of carbon, including transport by the atmosphere and ocean, must be in balance. The studies of Keeling, et al. [1989b], Tans et al. [1990], Enting, et al. [1993], and others, illustrate how this requirement provides information about the total budget of carbon. We have built on these earlier studies to obtain a new estimate of the anthropogenic carbon budget by least squares optimization of an initial estimate of the meridional distribution of sources and sinks so as to achieve a local balance in zonally integrated bands (reference [12]).

Initial estimates of the oceanic and atmospheric transport contributions are obtained by us from 3-D general circulation models (GCM's). Our atmospheric transport simulation makes use of the GFDL Tracer Transport Model. We have carried out a new simulation of oceanic uptake based on a slightly revised version of the non-seasonal primitive equation ocean general circulation model of Toggweiler, et al. [1989]. The model and results from it are described in detail by Sarmiento and Murnane (in preparation). We fix atmospheric $p\text{CO}_2$ at its pre-industrial value of 278 ppm adjusted to 100% humidity and allow it to invade the ocean until equilibrium is achieved. Concentrations for bicarbonate and carbonate ions are calculated following the procedure outlined by Peng, et al. [1987]. Organic matter production in the surface ocean is determined by forcing the model predicted phosphate towards the observed concentrations at the surface of the ocean (Najjar, et al. [1992]). The amount of carbon in the organic matter is determined by the Redfield ratio of 106 C to 1 P atom. New production is split equally between particulate and labile dissolved organic matter (POM and DOM, respectively). Regeneration of POM follows a power law scaling based on sediment trap observations (Najjar, et al. [1992]), while labile DOM is remineralized using a constant first order rate constant throughout the water column. The alkalinity and carbon involved in the CaCO_3 cycle are predicted using a Redfield ratio of 1 CaCO_3 to 5 organic carbon atoms. The depth distribution of CaCO_3 dissolution is determined by forcing the global mean vertical model alkalinity profile towards the observed global mean profile.

Our simulation of the pre-industrial air-sea flux component is shown in Table 3.

Table 3. Three estimates of the spatial distribution of oceanic sea-air fluxes of carbon dioxide. The Princeton Model results are from a study by Sarmiento and Murnane (in preparation).

	Tans et al. [1990]			Princeton Model	Keeling, et al. [1989b]
	(a)* Total air-sea flux	(b)** Perturbation	(a)-(b) Pre-industrial Flux	Pre-industrial Flux	Pre-industrial Flux
15°N-90°N	-0.59	-0.44	-0.16	-0.58	-1.68
15°S-15°N	+1.62	-0.54	2.16	1.21	1.83
90°S-15°S	-2.59	-0.93	-1.66	-0.63	-0.14
Total Imbalance	-1.56	-1.90	0.34	-0.00	0

* Combined pre-industrial and perturbation air-sea fluxes observed by Tans, et al. [1990]

** Air-sea flux due to the anthropogenic perturbation as calculated by Sarmiento, et al. [1992]

We can compare the results of this model to an estimate of the distribution inferred from measurements of present air-sea exchange such as those of Tans, et

al. [1990] by subtracting off the model estimated fossil CO₂ uptake component described below. The air-sea fluxes thus estimated are shown in Table 3. The total sum of 0.35 Pg C/yr is non-zero due to the mismatch between Tans et al.'s total oceanic uptake estimate and that of Sarmiento, et al. [1992]. Also shown in Table 3 is an estimate by Keeling, et al. [1989a], obtained from a consideration of the overall carbon budget in conjunction with the atmospheric transport constraint discussed previously. This is similar to scenarios 5 through 8 of Tans, et al. [1990].

The three pre-industrial air-sea flux estimates of Table 3 give a dramatic illustration of the present depth of our ignorance regarding the pre-industrial ocean carbon cycle. Tans, et al. [1990] show a large equatorial efflux balanced primarily by uptake in the southern hemisphere. Murnane and Sarmiento's equatorial efflux is balanced by an equal uptake in both hemispheres. The equatorial efflux of Keeling, et al. [1989a] is balanced by a northern hemisphere uptake. A further difference between the three results is that the equatorial efflux of Sarmiento and Murnane is much smaller than those of the other studies. Each of these estimates is subject to great uncertainty. A major task of future research will be to attempt reconciliation of the various constraints on the spatial distribution of the air-sea flux.

Simulations of pre-industrial air-sea fluxes such as those we show in Table 3 are very challenging due to the high sensitivity of air-sea fluxes to the heat flux and the difficulty of predicting the biological pump. The low equatorial efflux in this model may be caused by the unrealistically high temperature of thermocline waters predicted by the model. As a consequence, upwelling waters would have a lower CO₂ load than they would have if they had left the surface with colder temperatures. On the other hand, we shall see later that other constraints on the carbon budget combine to give an excess source at the Equator. It would thus be difficult to accommodate a larger oceanic source. The large magnitude of the Princeton model flux into the southern hemisphere ocean as contrasted with the Keeling et al. scenario may also be a result of difficulties in properly simulating the temperature history of waters. Our ocean circulation model has too much southwards transport of upper ocean waters in the South Indian Ocean. These waters, when cooled, would provide a CO₂ sink, thus offsetting the natural tendency of the Southern Ocean to be a source of CO₂ to the atmosphere due to upwelling of CO₂ rich waters and convective overturning. The present difficulty in predicting the northward flux of heat and thermohaline overturning in the North Atlantic almost certainly has an impact on the meridional transport of carbon by the oceans.

Initial estimates of the meridional distribution of the sources (fossil fuel burning, cement production, and land use changes) are obtained from Tans, et al.

[1990]. Terrestrial uptake is apportioned according to the net primary production of Melillo, et al. [1993], with the assumption that CO₂ fertilization would behave approximately in this fashion. The local budget of the initial estimates is internally consistent north of 30°N, requiring only a modest correction to arrive at the final result. This result is consistent with CO₂ fertilization as the main mechanism for terrestrial uptake. If nitrogen fertilization were dominant, one would expect the uptake to be more biased towards the northern hemisphere regions where fossil emissions occur. Such a bias would give too large a sink in this region. The prior estimates in the tropics give too large a source, and those in the southern hemisphere give too large a sink. We carry out a least squares optimization of the spatial distribution of sources and sinks, requiring that the local budget be balanced. The large excess tropical source is corrected primarily by reducing deforestation. The excess southern hemisphere sink is corrected primarily by reducing oceanic uptake in that region. The prior and corrected estimates of the global integral of the source and sink terms is given in Table 4 (details of these results are discussed in [12]. Note the large drop in the deforestation and land use term accompanied by reductions in oceanic and terrestrial uptake.

Table 4. A revised estimate for the anthropogenic carbon budget obtained by requiring that the budget be balanced locally as well as globally (Reference [12]).

	Initial estimate	New estimate
Fossil Source (F)	5.4±0.5	
Atmospheric Increase (A)	<u>-3.2±0.2</u>	
Remainder (R=F-A)	2.2±0.5	2.2±0.4
Ocean Uptake	-1.9±0.6	-1.5±0.5
Deforestation & Land Use	1.6±1.0	0.6±0.6
Terrestrial Uptake	-1.9±1.0	-1.3±0.6

(units=Pg C/yr).

B.- Predicting the Future

One of the major activities of our group during the last year was our participation in the model comparison study of Enting, et al. [1994] carried out in preparation for the IPCC 1994 report. The objective of this study was to estimate the oceanic and terrestrial uptake that would occur in the scenarios of Figure 2.

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Figure 2. Scenarios for future atmospheric CO₂ contents used in the 1994 IPCC model comparison study (Enting, et al. [1994]).

The primary constraint we have on the combined effect of these two processes is the time history of Figure 1. Figure 1b shows our fit to the missing sink data of a simple terrestrial model that includes fertilization by the increased atmospheric content of CO₂, as well as sensitivity of the rate of remineralization to temperature (reference [13]). Figure 3 shows how much carbon dioxide would be taken up by our simple terrestrial model and the ocean model of Sarmiento, et al. [1992] for the IPCC scenarios of Figure 1 (reference [11]). The terrestrial and oceanic sinks are comparable in magnitude and together completely dominate the anthropogenic carbon budget, particularly after about a century when the growth of atmospheric CO₂ stops.

Figure 3. Combined effect of oceanic and terrestrial uptake in the S750 (upper panel) and S450 (lower panel IPCC scenarios of Figure 1 (Sarmiento, LeQuéré, and Pacala, submitted).

Perhaps the major source of uncertainty in predictions of the future oceanic carbon dioxide uptake capacity such as those of Figure 3 lies in our ability to correctly simulate the response of ocean circulation to climate change. The coupled atmosphere-ocean model study of Manabe and Stouffer [1993b], shows an almost total collapse of North Atlantic Deep Water formation and a considerable deepening of the thermocline in a CO_2 doubling and quadrupling greenhouse warming simulation. Such changes in ocean circulation would have a major impact on oceanic uptake of carbon dioxide and on the behavior of the biological pump.

The "biological pump" removes organic carbon from the surface to the deep ocean. On a global scale, this downward flux is closely matched by a return flux of dissolved inorganic carbon formed by remineralization of the organic matter in the abyss. River fluxes and sediment burial contribute a small portion of the carbon involved in this cycle. Ice core observations showing that atmospheric pCO_2 was nearly constant for 9 centuries prior to the Industrial Revolution (Siegenthaler, et al. [1988]) strongly suggest that the fluxes controlling the surface ocean total carbon content were in balance. This balance is assumed to have continued through the Industrial Revolution, thus relieving us of the need to consider the role of the biological pump in anthropogenic carbon uptake by the oceans.

It is extremely difficult to assess how the biological pump will respond to future greenhouse climate warming effects such as the change in ocean circulation of Manabe and Stouffer [1993b]. The following table summarizes results from century long sensitivity studies by Sarmiento and Orr [1991] in

which the biological pump was assumed to totally deplete major nutrients in surface regions that today have an excess. This is one possible scenario for the response of the biological pump to the impact of greenhouse warming on oceanic processes. How realistic such a scenario would be is speculative. The reasons for the existence of these so-called "high nutrient-low chlorophyll" regions is the subject of intense research at present. The baseline simulation of the Sarmiento and Orr [1991] study has a "business-as-usual" fossil CO₂ flux to the atmosphere. The perturbation pCO₂ signal is calculated by subtracting the baseline simulation from scenarios in which surface nutrients are depleted over the latitude band given in the table. Carbon is removed in proportion to the average carbon to nutrient ratio in organic matter.

Latitude band of nutrient depletion	Atmospheric pCO ₂ perturbation (ppm/100 yr)
North Atlantic (31.12°N to 80.06°N)	-12.7
North Pacific (31.12°N to 66.69°N)	-7.0
Equatorial Region (18°N to 18°S)	-2.8
Southern Ocean (South of 31.12°S)	-71.9

The potential impact of these nutrient depletion scenarios is quite large. Results such as these suggest that it is essential for us to gain a better understanding of the biological pump. Our progress on research in this difficult area has been substantial (references [1], [2], [3], [4], [8], and [10]). We have succeeded in placing an ecosystem model into an ocean GCM and have carried out a large number of sensitivity studies in order to improve these models. Our greatest progress has been in areas funded by NASA and JGOFS/NSF, where we have successfully assimilated satellite observations and developed a vastly improved ecosystem model that is able to fit observations at the time series stations.

II.- Goals for Year 2

A.- Understanding the Anthropogenic Carbon Budget

We will complete our study of the spatial distribution of oceanic sources and sinks. We will complete our study of the implications of atmospheric transport for the spatial distribution of oceanic as well as terrestrial sources and sinks. We will further pursue our study of the temporal history of the terrestrial sink. We will add the carbon-13 constraint to our oceanic and atmospheric transport studies. Sarmiento will be visiting Bern, Switzerland for the next academic year, where he will have the opportunity to bring together the Bern and Princeton research efforts. We are particularly interested in developing a strategy to improve the agreement between the various ocean air-sea flux

constraints shown in Table 3. This will be pursued in part by a closer collaboration with observationalists such as Taro Takahashi.

B.- Predicting the Future

We will continue our research into how to simulate the ocean biological pump. We will complete our first simulation of oceanic uptake in the coupled model of Manabe and Stouffer [1993a], investigating how the collapse of thermohaline circulation and deepening of the thermocline affect oceanic uptake.

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