SIMULATIONS OF THE GLOBAL CARBON CYCLE AND
ANTHROPOGENIC CO₂ TRANSIENT

FINAL REPORT

For the period September 15, 1993 – September 14, 1997

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"Simulations of the Carbon Cycles in the Oceans"

Abstract

This final report summarizes work that was carried out over a period of 4 years from 9/15/93 to 9/14/97 under DOE grant DE-FG02-90ER61052. The primary accomplishment of this grant was the development of an ocean biogeochemistry model for the carbon cycle, and the application of this model to studies of anthropogenic CO₂ uptake and the global carbon cycle. The model has been used to study the oceanic uptake that would occur if future atmospheric CO₂ were to be stabilized with the ocean circulation remaining constant (IPCC 1995). We also modeled how oceanic uptake would be affected by changes in ocean circulation that are predicted to occur due to global warming. The research resulted in 21 publications, and an additional 5 papers either in press or in preparation. The accomplishments of this grant served as the foundation on which the Carbon Modeling Consortium was built. The CMC is a NOAA funded collaborative program involving Principal Investigators from various NOAA laboratories and universities. It has the goal of developing techniques to monitor the global carbon cycle on land as well as the ocean, and to predict its future course.

I.- Publications

Twenty papers and one Ph.D. thesis were published during the period of this grant. One additional paper is in press and four are in preparation reporting on work that was completed during the period of this grant. The following list of publications is separated into two sections: one on understanding the anthropogenic budget, and the other on predicting the future carbon budget, including the development of models for that purpose. This follows the organization of the final report that follows.

A.- Understanding the Anthropogenic Carbon Budget

- Reprint*
- [1] ✓ Gruber, N, J. L. Sarmiento, and T. F. Stocker, 1996. An improved method for detecting anthropogenic CO₂ in the oceans. *Global Biogeochem. Cycles*, 10: 809-837.
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 - [4] Murnane and J.L. Sarmiento, 1998. Rapid change in the $\delta^{13}\text{C}$ of atmospheric CO₂ between 1970 and 1990 (in preparation).
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- [13] P. Suntharalingam, J.L. Sarmiento, and J.R. Toggweiler, 1998. The global significance of nitrous oxide production and transport from the oceanic low oxygen zones, *Global Biogeochemical Cycles*, (in prep.).
- [14] P. Suntharalingam, and J.L. Sarmiento, 1998. Spatial variability of the surface oceanic nitrous oxide distribution: An analysis with Multi-variate Adaptive Regression Splines, *Global Biogeochemical Cycles* (in prep.).

B.- Predicting the Future

- [15] Anderson, L. A., and J. L. Sarmiento, 1994. Redfield ratios of remineralization determined by nutrient data analysis. *Global Biogeochem. Cycles*, 8: 65-80.
- Reprint [16] ✓ Anderson, L., and J. L. Sarmiento, 1995. Global ocean phosphate and oxygen simulations. *Global Biogeochem. Cycles*, 9: 621-636.
- [17] 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.
- Reprint [18] ✓ Figueroa, H. A., 1996. World ocean density ratios. *J. Phys. Oceanogr.*, 2: 267-275.
- Reprint [19] ✓ Joos, F., M. Bruno, R. Fink, U. Siegenthaler, T. F. Stocker, C. Le Quéré, and J. L. Sarmiento, 1996. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus*, 48B: 397-417.

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- [20] 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.
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 - [23] ✓ Sarmiento, J. L., and C. Le Quéré, 1996. Oceanic CO₂ uptake in a model of century-scale global warming. Science, 274: 1346-1350.
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II.- Final Report

A.- Understanding the Anthropogenic Carbon Budget

The discussion of the anthropogenic carbon budget is organized around four topics: (1) the globally integrated budget at the present time, (2) the time history of the carbon budget, (3) the spatial distribution of carbon fluxes, and (4) simulating the distribution of related tracers. A description of our research in each of these areas is given in the following four sub-sections.

(1) Globally integrated budget

A series of five review papers aimed at different audiences ([2], [6],[7], [8], and [10]) report on our present understanding of the globally integrated anthropogenic carbon budget, with particular reference to the role of the oceans in that budget. Publication [2] was published in a German language journal with wide readership by German physicists; publication [6] was published in the journal of the American Chemical Society; publication [7] was published by the Institute of International Studies at Berkeley; publication [8] was published in an important biological journal; and publication [10] was published in Nature. Although all these review papers also make use of original research results sponsored by this grant, the main

emphasis of our research on the anthropogenic carbon budget has been on the less well understood temporal variability and spatial pattern of the carbon sources and sinks. These results are reported in the following sections.

(2) Temporal history

Our most important analysis of the time evolution of the anthropogenic carbon budget is described in publication [24], in which a new single deconvolution of the global carbon budget was carried out for the period from 1850 until the present. The atmospheric increase was constrained by observations, the oceanic uptake was estimated using our ocean GCM model, and deforestation and land use changes were constrained by previously published estimates. The residual was assumed to result from terrestrial biotic uptake due to CO₂ fertilization and response to warming, and modeled as such. The model parameters were estimated by a least squares fit to the estimated residual. This model was then used for simulations of the IPCC CO₂ stabilization scenarios as described below.

Publication [5] is a Nature News and Views article on the stalling of the atmospheric growth rate that occurred at the time of the Mount Pinatubo eruption.

(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. [1989], Tans et al. [1990], Enting, et al. [1993], and others, illustrate how this requirement provides information about the total budget of carbon. We have studied the spatial distribution of oceanic sources and sinks by developing and analyzing ocean GCM models ([3] and [9]) and by analyzing oceanic observations ([1]). In publication [1] we describe a new method we developed for extracting the anthropogenic CO₂ signal out of the total dissolved inorganic carbon.

An important outgrowth of our DOE sponsored research on the spatial distribution of sources and sinks was our decision to combine with a number of investigators at other institutions who are measuring carbon in the atmosphere and ocean to form the Carbon Modeling Consortium with support from NOAA. The CMC has been active for 2 1/2 years. One of our major achievements is an estimate of terrestrial source and sink distributions based on a singular value decomposition analysis of atmospheric CO₂ measurements and GCM models. The oceanic model developed with our DOE support played a major role in this study.

(4) Related tracers

Our ocean model of the carbon cycle has been used to reproduce the pre-industrial steady state distribution of and $\delta^{13}\text{C}$. The results of this work are being written up at present ([4]). The ocean model was also used to study the distribution of the powerful greenhouse gas, nitrous oxide ([11]) and several papers are in preparation that describe the results of the model simulation and a new estimate of the air-sea N_2O flux based on analysis of ocean N_2O observations ([12], [13], and [14]). Model scenarios of total carbon and $\delta^{13}\text{C}$ are used to show the relative importance of the solubility pump and the biological pump for air-sea exchange of carbon and its isotopic signal. The isotopic signal can be used as an independent constraint on the global carbon cycle. We added nitrous oxide to our project because of its importance as a greenhouse gas with increasing atmospheric concentration, and because the ocean models we have developed can be readily adapted to the study of the oceanic source of this gas.

B.- Predicting the Future

Perhaps the major source of uncertainty in predictions of the future oceanic carbon dioxide uptake capacity 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 [1993], 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.

(1) Model development

The development of models starts with an understanding of observations. The basis for all ocean biogeochemistry models at present is some sort of assumption about the stoichiometric relationship between the various major constituents of organic matter, namely C:N:P:O₂. We did a careful analysis of the observed distributions of relevant tracers to estimate these ratios ([15]). We also used the ratios in the technique we developed to estimate the anthropogenic carbon inventory of the ocean ([1]).

The simulation of organic matter cycling in the ocean requires a model of organic matter formation in the upper ocean and its remineralization at all depths of the ocean. Publications [17], [25], and [26], report on our progress on the development of an ecosystem model for surface ocean processes. Publications [20], [21], and [22], report on our analysis of trace metal observations in order to elucidate the cycling of particles in the water column. Publication [18] describes some of the research our group did on relevant aspects of the physical oceanographic setting.

All of the above research and other earlier research has culminated in the development of a new ocean biogeochemistry model. The first version of this was described in [16]. The latest version is described in [3] and [9]. This ocean model is presently being used by the Carbon Modeling Consortium for a wide range of carbon cycle problems, and also served as the basis for the scenario studies described in the following section. An additional valuable achievement was the development of a new Green's function approach that will enable us to represent the uptake of anthropogenic carbon and isotopes for a steady state ocean circulation ([19]). This Green's function makes use of a pulse placed in the mixed layer of the ocean rather than the atmosphere. This eliminates the difficulty with the non-linearity of the chemistry in the transition from the atmosphere to the ocean that had plagued earlier efforts.

(2) Scenarios

One of the major activities of our group was our participation in the model comparison study of Enting et al. [1994] carried out in preparation for the IPCC 1995 report. The objective of this study was to estimate the limits on anthropogenic CO₂ emissions that would be required in order to stabilize future atmospheric CO₂. We used our models to estimate the oceanic and terrestrial uptake that would occur for the specified range of future stabilization scenarios for atmospheric CO₂. This work is described in publication [24].

The other major accomplishment of our group was to emplace the ocean biogeochemistry model in the ocean component of the Manabe and Stouffer [1993] atmosphere-ocean coupled model. This model shows a dramatic collapse of the deep thermohaline circulation in response to global warming. The impacts of this were first described in [23], and numerous follow-up studies are occurring now as part of the Carbon Modeling Consortium.

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Manabe, S. and R. J. Stouffer, Century-scale effects of increased atmospheric CO₂ on the ocean-atmosphere system, *Nature*, 364, 215-218, 1993.

The Terrestrial Carbon Cycle: understanding the spatial distribution of sources and sinks

May 29, 1998

1 Abstract

The report summarizes the work carried under DOE grant # DE-FG02-90ER61052 from 1996 to 1997. The funds provided by DOE enabled us to make substantial progress in understanding of CO₂ exchanges between the atmosphere and the terrestrial biosphere. The primary achievements of the grant were threefold. First, using inversion techniques, we determined how the Northern Hemisphere terrestrial carbon sink is partitioned between the American continent and Eurasia. Second, results from inversions using GTEC, the process based model of terrestrial-biosphere developed by researchers at DOE, were used to improve the seasonality of terrestrial CO₂ fluxes in the GTEC model. Third, we have developed a general method for scaling of physiological models of individual plant growth to larger scales. This formal mechanistic scaling takes account of disturbance processes, height structure and biodiversity within plant

communities. Using this scaling procedure, we are now in a position to investigate the consequences of sub-grid scale heterogeneity within terrestrial ecosystems, including analyzing the impacts of human land-use and land-use change.

2 Resulting Publications

- [1] Fan, S.M., M. Gloor, J. Mahlman, S.Pacala, J. Sarmiento, T. Takahash & P. Tans. Atmospheric and Oceanic CO₂ data and models imply a large terrestrial carbon sink in North America. *Science*, (submitted).
- [2] Hurtt, G.C., P.R. Moorcroft, S.W. Pacala & S.A. Levin. Terrestrial models and global change: challenges for the future. *Global Change Biology* (in press).
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- [4] Post, W.M., P.R. Moorcroft, M. Gloor, S.W. Pacala, A.W. King, S.D.Wullschleger, S.M. Fan. & J.L. Sarmiento 1997. Using terrestrial models to examine the use of atmospheric monitoring network data to infer terrestrial carbon fluxes and validate terrestrial carbon models. Ecological Society of America, Annual Meeting, Albuquerque, NM.

3 Final Report

As proposed, we integrated DOE ecosystem model GTEC into the GFDL tracer transport model GCTM and ran tracer transport simulations to obtain the basis functions for the GTEC model.

The results of this work were presented at the Ecological Society of America annual meeting (Post et al., 1997).

The basis functions for GTEC describe spatial and temporal distribution of atmospheric CO₂ resulting from with terrestrial uptake and release of CO₂ predicted by the GTEC model. Comparison of the predicted seasonal trends in CO₂ concentrations, with observations from the Global-View stations, revealed that the seasonality in net ecosystem production in the GTEC model was too weak. In the light of these findings, researchers at DOE currently working to improve the seasonality in the GTEC model. Because of the discrepancy between predicted and observed seasonality in the terrestrial CO₂ signal, we were unable to use GTEC basis functions to infer the spatial distribution of CO₂ sources and sinks. However, we proceeded with the inverse modeling study using the CASA satellite-derived terrestrial ecosystem model, whose basis functions had been obtained previously, using NOAA funds.

The inversion study yielded several interesting results which have been submitted for publication. Most significantly, the inversion identified that the Northern Hemisphere sink identified by Tans *et al* (1990) , appears to be predominantly in North America. The sink estimate for North America is 1.7 ± 0.5 Pg, a figure close to size of North American fossil fuel release.

As outlined in the proposal, we developed a general methodology for including biodiversity, land-use, and other forms of sub-grid-scale heterogeneity into terrestrial ecosystem models. The scaling procedure uses partial differential equations to approximate the ensemble mean behavior of stochastic individual-based plant competition. The equations correctly predict the ensemble mean output of the plant simulator SORTIE and is currently being checked against the behavior of a broad class of individual-based plant simulators. The model framework will accommodate

mechanistic physiological sub-models that governing individual plant performance that are present in new version of GTEC being developed by researchers at DOE.

The scaling methodology is able to incorporate multiple axes of biodiversity and multiple forms of sub-grid scale heterogeneity such as land use, soil type and topography . We are using this framework to develop a new large-scale version of a terrestrial ecosystem model, which will allow data collected at multiple spatial and temporal scales to be correctly used in model parameterization. A paper describing outlining this methodology is currently in review (Hurt et al. in review), and will form the basis two papers in preparation. In addition on the basis of these results, we are now a science team participating the Large-scale Biosphere Atmosphere experiment in Amazonia (LBA).

Finally, while awaiting improvements in GTEC model, we studied potential consequences of climate change for carbon uptake by terrestrial ecosystems and vegetation patterns using other currently available terrestrial models. This work was presented at the annual meeting of the Carbon Modeling Center this past summer (Hurt, 1997), and is now being prepared for publication. Preliminary results from this study suggest that the potential biogeographic consequences of future climate change appear much larger than the potential carbon consequences. For example, using a Holdridge-based life zone model with associated above-ground and below-ground carbon pools, 58% of the land surface changes life-zone classification under GFDL coupled-modeled 4X CO₂ conditions, while potential terrestrial carbon storage increases by only 0.6%.

4 References

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