FINAL REPORT DOE/ER/61054--T2

# SIMULATIONS OF THE GLOBAL CARBON CYCLE AND ANTHROPOGENIC CO2 TRANSIENT

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## DISCLAIMER

# 1 Abstract

The major emphasis of our DOE funded research was to study the redistribution of anthropogenic carbon in the climate system and to constrain the global budgets of anthropogenic carbon and the carbon isotopes $^{13}C$ and $^{14}C$ for the historical period. We have continued the development of box models of the ocean carbon cycle (HILDA model) and the land biota. The coupled model (Bern model) was chosen as the reference model for scenario calculations and the calculations of global warming potential by the Intergovernmental Panel on Climate Change. These models were applied (1) to estimate the uptake of anthropogenic carbon by the ocean and the land biosphere for the last 200 years; (2) to investigate uncertainties in deconvolved fertilization fluxes into the land biota due to uncertainties in ice core $CO_2$ data; (3) to study the relationship between future atmospheric $CO_2$ levels and carbon emissions; (4) to investigate the budgets of bomb-produced radiocarbon and fossil $^{13}C$. We assessed the utility of bomb-produced and natural $^{13}C$ observations to validate ocean models of anthropogenic $CO_2$ uptake and tested the eddy diffusion parameterization of large-scale vertical transport in ocean box models. For this, vertical tracer transport in box-diffusion models and the 3-D ocean general circulation model from GFDL/Princeton was compared. We analyzed the distribution of the conservative property $\Delta C^*$ to obtain a direct estimate based on marine measurements of the uptake of anthropogenic $CO_2$ by the North Atlantic. We contribute to the missing sink debate by using atmospheric $CO_2$ and $^{13}C$ levels to disentangle the net carbon fluxes into the land biota and the ocean. A simplified representation for 4 different ocean models of anthropogenic $CO_2$ uptake based on mixed-layer pulse response functions was developed. The same pulse response model was applied to simulate the heat uptake by the ocean and to run transient global warming scenarions. These pulse substitute models are already used by several groups involved in biospheric carbon cycle modeling and in integrated assessment studies.

# Contents

# 2 Preamble

In July 1994 Prof. Uli Siegenthaler lost his battle with cancer. We are deeply saddened by the loss of our esteemed colleague and friend. U. Siegenthaler was Principal Investigator of the two previous grant. After his death, Prof. Thomas Stocker (Head Climate and Environmental Physics) and Dr. Fortunat Joos (Leader Carbon Cycle Group) took the responsibility for the project.

From August 1994 to July 1995 Prof. Jorge Sarmiento from the Atmospheric and Oceanic Science Program, Princeton, was a visiting Professor at the Physics Institute, University of Bern. During that time we have collaborated intensively on a number of subjects related to our DOE proposal.

# 3 Accomplishments

## 3.1 Publications since January 1990

11 papers and 1 Ph.D. thesis which are related to DOE funded research have been completed during the period of Grant # DE-FG02-90ER61054 (Sep. 1993 - Sep. 1996). Additionally, 9 publications and 1 Ph.D. thesis has been completed during the 1990-1993 period. (Grant #DE-FG02-90ER61052). Furthermore, we have presented several abstracts at international meetings.

### 3.1.1 Published

**1990-93:**


[1] F. Joos. *Modellierung der Verteilung von Spurenstoffen im Ozean und des globalen Kohlenstoffkreislaufes.* Ph.d. thesis, University of Bern, 1992.

[2] F. Joos, J. L. Sarmiento, and U. Siegenthaler. Estimates of the effect of Southern Ocean iron fertilization on atmospheric $CO_2$ concentrations. *Nature*, 349:772–774, 1991.

[3] F. Joos, U. Siegenthaler, and J. L. Sarmiento. Possible effects of iron fertilization in the Southern Ocean on atmospheric $CO_2$ concentration. *Global Biogeochemical Cycles*, 5(2):135–150, 1991.

[4] J. L. Sarmiento, J. C. Orr, and U. Siegenthaler. A perturbation simulation of $CO_2$ uptake in an ocean general circulation model. *J. Geophys. Res.*, 97(C3):3621–3645, 1992.

[5] J. L. Sarmiento and U. Siegenthaler. New production and the global carbon cycle. In P. G. Falkowski and A. D. Woodhead, editors, *Primary Productivity and Biogeochemical Cycles in the Sea*, pages 317–332. Plenum Press, 1992.

[6] U. Siegenthaler. El Niño and atmospheric $CO_2$. *Nature*, 345:295–296, 1990.

[7] U. Siegenthaler. Modelling the present-day oceanic carbon cycle. In M. Heimann, editor, *The Carbon Cycle*. Springer Verlag, 1993.

[8] U. Siegenthaler and F. Joos. Use of a simple model for studying oceanic tracer distributions and the global carbon cycle. *Tellus*, 44B:186–207, 1992.

[9] U. Siegenthaler and J. L. Sarmiento. Atmospheric carbon dioxide and the ocean. *Nature*, 365:119–125, 1993.

[10] P. Tett, G. Jackson, F. Joos, P. Nival, J. Rodriguez, and U. Wolf. Modelling particle fluxes. In G.T. Evans and M.J.R. Fasham, editors, *Towards a model of ocean biogeochemical processes*, volume 10, pages 227–236. Springer Verlag, 1993.

**1994-96:**

[1] R. Fink. *Zur Kohlenstoffchemie des Ozeans und zur Modellierung des natürlichen Kohlenstoffkreislaufes*. PhD thesis, University of Bern, 1996.

[2] F. Joos. Imbalance in the budget. *Nature*, 370:181–182, 1994.

[3] F. Joos. Kommentar zum Artikel: Zur ozeanischen Pufferwirkung auf den atmosphärischen $CO_2$ Gehalt in einem Fliessgleichgewicht. *Journal für praktische Chemie / Chemiker Zeitung*, 336:280–282, 1994.

[4] F. Joos, M. Bruno, R. Fink, T. F. Stocker, U. Siegenthaler, C. Le Quéré, and J. L. Sarmiento. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus*, 48B:397–417, 1996.

[5] F. Joos and J. L. Sarmiento. Der atmosphärische $CO_2$-Anstieg. *Physikalische Blätter*, 51:405–411, 1995.

[6] D. Schimel, D. Alves, I.G. Enting, M. Heimann, F. Joos, D. Raynaud, and T.M.L. Wigley. $CO_2$ and the carbon cycle. In J.T. Houghton, editor, *IPCC Second Scientific Assessment of Climate Change*, pages 76–86. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (UK), 1996.

[7] D. Schimel, I.G. Enting, M. Heimann, T.M.L. Wigley, D. Raynaud, D. Alves, and U. Siegenthaler. $CO_2$ and the carbon cycle. In J.T. Houghton, L.G. Meira-Filho, M. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell, editors, *Climate Change 94, Radiative Forcing of Climate Change*, pages 38–71. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (UK), 1994.

### 3.1.2 In Press or submitted

[1] M. Bruno and F. Joos. Revised estimate of the biospheric carbon sink: A Monte Carlo simulation deconvolving the atmospheric $CO_2$ history. *Global Biogeochemical Cycles*, 1996. submitted.

[2] N. Gruber, J. L. Sarmiento, and T. F. Stocker. An improved method to detect anthropogenic $CO_2$ in the oceans. *Global Biogeochemical Cycles*, 1996. in press.

[3] F. Joos. The atmospheric carbon dioxide perturbation. *Europhysics News*, 1996. in press.

[4] F. Joos and M. Bruno. Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric $CO_2$ and global warming. *Physics and Chemistry of the Earth*, 1996. submitted.

[5] F. Joos. J. C. Orr, and U. Siegenthaler. Ocean carbon transport in a box-diffusion versus a general circulation model. *J. Geophys. Res.*, 1996. In press.

## 3.2 Summary of Results (1993-96)

### 3.2.1 Substitutes of Oceanic and Biospheric Carbon Cycle Models

One of the major aims of this grant was to develop simple representations of complex oceanic models of anthropogenic $CO_2$ uptake. As an unexpected addition to our proposal, we have also built a substitute model for a terrestrial biosphere model [*Joos et al.*, 1996]. These substitute models run extremely fast and are easy to code. We are presently using substitute models of HILDA, a 2-D model and the GFDL-Princeton 3-D model to perform Monte Carlo simulations (see below) and to run scenario calculations linking anthropogenic emissions and atmospheric $CO_2$ concentrations. At other institutes, our substitute models are already used for integrated assessment studies or in connection with land biota models.

Establishing the link between atmospheric $CO_2$ concentration and anthropogenic carbon emissions requires the development of complex carbon cycle models of the primary sinks, the ocean and terrestrial biosphere. Once such models have been developed the potential exists to use pulse response functions to characterize their behavior. However, the application of response functions based on a pulse increase in atmospheric $CO_2$ to characterize oceanic uptake, the conventional technique, does not yield a very accurate result due to nonlinearities in the aquatic carbon chemistry.

We proposed the use of an ocean mixed-layer pulse response function that characterizes the surface to deep ocean mixing in combination with a separate equation describing air-sea exchange. The use of a mixed-layer pulse response function avoids the problem arising from the nonlinearities of the carbon chemistry and gives therefore more accurate results. The response function is also valid for tracers other than carbon. We found that tracer uptake of the HILDA and Box-Diffusion model can be represented exactly by the new method. For the Princeton 3-D model, we find that the agreement between the complete model and its pulse substitute is better than 4% for the cumulative uptake of anthropogenic carbon for the period 1765 to 2300 applying the IPCC stabilization scenarios S450 and S750 and better than 2% for the simulated inventory and surface concentration of bomb-produced radiocarbon (Fig. 1). By contrast, the use of atmospheric response functions gives deviations up to 73% for the cumulative $CO_2$ uptake as calculated with the Princeton 3-D model.

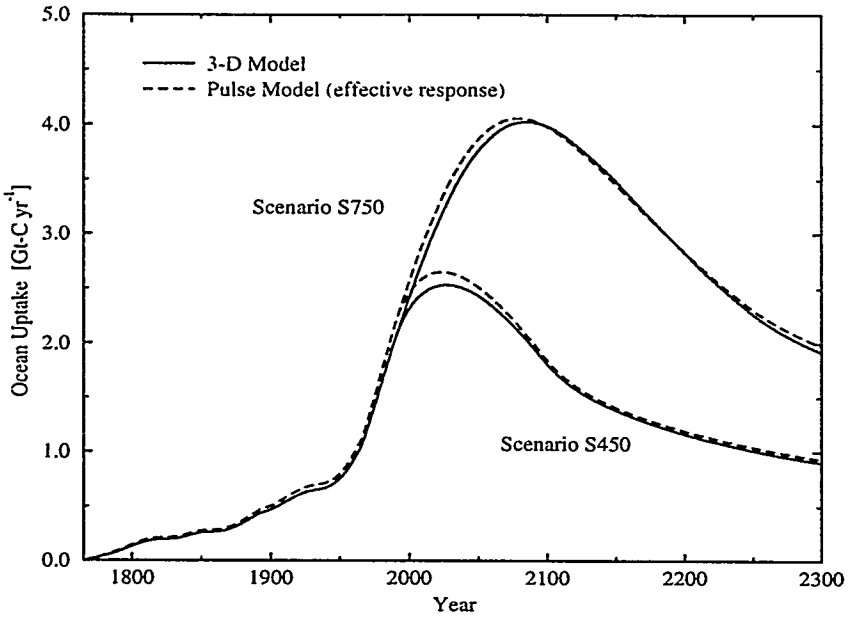


Figure 1: *Oceanic uptake of anthropogenic carbon for two different scenarios as simulated with the Princeton 3-D carbon cycle model (solid line) and its mixed-layer pulse response substitute model [Joos et al., 1996]. Atmospheric $CO_2$ concentrations are prescribed in order to stabilize concentration at 450 and 750 ppm (IPCC stabilization profiles S450 and S750 [Houghton et al., 1994]).*

The use of a decay response function is introduced for calculating the potential carbon storage on land as a substitute for terrestrial biosphere models that describe the overturning of assimilated carbon. This, in combination with an equation describing the net primary productivity permits us to exactly characterize simple biosphere models. As the time scales of biospheric overturning are one key aspect to determine the amount of anthropogenic carbon which might be sequestered by the biosphere, we suggest that decay response functions should be used as a simple and standardized measure to compare different models and to improve understanding of their behavior.

### 3.2.2 The Transient Response of Surface Temperature and Ocean Thermal Expansion to Changes in Radiative Forcing

Adequately designed spatially aggregated models can be used to calculate the relationship between anthropogenic carbon emissions, atmospheric $CO_2$ levels and simple climate indicators such as global average surface warming and oceanic thermal expansion. This is essential to perform integrated assessment of global change and cost-efficient scenario calculations.

We have applied the HILDA model in its pulse subsitute version (see previous section) to calculate global heat uptake by the ocean, its thermal expansion, and trends in global average surface temperature. The air-sea coupling is described following Siegenthaler and Oeschger(1984). A coupling constant of 6.3 W $m^{-2}$ is used for the logarithmic relationship between $CO_2$ and radiative forcing. The fraction covered by land is 0.29 and the heat exchange coefficient between land and continent is set to 7.2 W $m^{-2}$ $K^{-1}$ , corresponding to

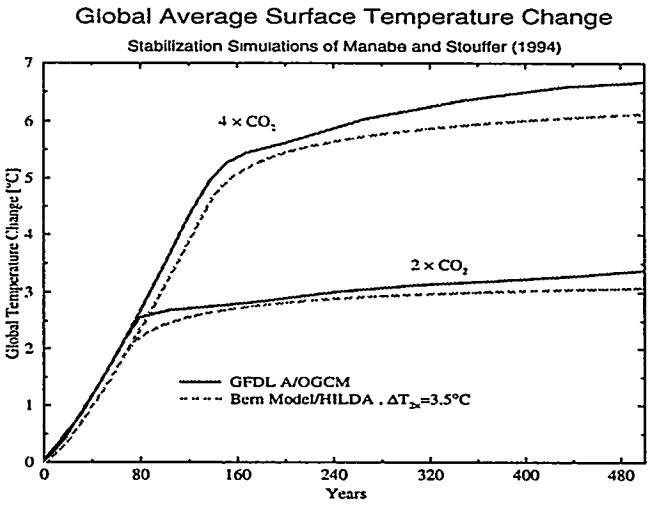


Figure 2: *Global average surface temperature warming of the GFDL A/OGCM as compared with results of the HILDA model.*

an atmospheric relaxation time of 8 days. The equilibrium response of the model for a given radiative forcing, say for a doubling of pre-industrial $CO_2$ is not modeled but prescribed according to results of atmosphere general circulation models. The ratio of the climate sensitivities over land and ocean is chosen in order to obtain a 30 % warmer equilibrium response over land than over the sea. As a standard, the global climate sensitivity is set to 2.5 K for an increase in radiative forcing corresponding to a doubling of preindustrial atmospheric $CO_2$ ($\Delta T_{2x}CO_2$)=2.5 K).

In the Second Scientific Assessment of IPCC the results of 10 atmosphere/ocean general circulation models (A/OGCMs) are compared for an increase in radiative forcing by 1 % $yr^{-1}$ [*Houghton et al.*, 1996, Figure 6.4]. We have also calculated the corresponding response of the HILDA model applying climate sensitivities of 2.1 and 4.6 K for doubling of $CO_2$, thereby bracketing the sensitivities of the 10 A/OGCMs. After 80 years, the increase in global average surface temperature is 1.6 K and 2.4 K, respectively. This compares well with the results of nine A/OGCMs (excluding one outlier) which are in the range of 1.5 to 2.7 K. The HILDA model was also compared to the $2xCO_2$ and $4xCO_2$ stabilisation simulations of [*Manabe and Stouffer*, 1994]. Here, we applied the climate sensitivity of 3.5 K of the GFDL model. The HILDA model lags the temperature reponse of the GFDL A/OGCM by a few tenths of a degree. Thermal expansion is also smaller in the HILDA model. This lower response of the HILDA model can be explained by its faster surface-to-deep mixing as compared to the GFDL model. Differences between results of the two models are less than 15 % for globally averaged surface temperature and less than 25 % for ocenic thermal expansion (Fig. 2 and Fig. 3). This is within the range of uncertainties associated with such calculations. To conclude, results of the HILDA model in general agree with results of other A/OGCMs. It is worth to note that ocean mixing in the Bern model has not been tuned to match any other model, rather its parameters have been derived from the observed distribution of oceanic tracers.

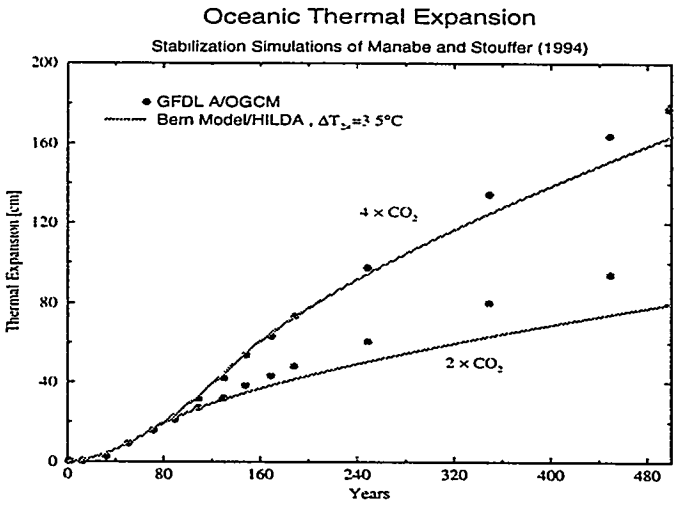


Figure 3: *Sea level rise due to thermal expansion of the GFDL A/OGCM as compared with results of the HILDA model.*

### 3.2.3 The Global Budget of Bomb-Produced Radiocarbon and $^{13}C$

Besides the budget of anthropogenic $CO_2$ any carbon cycle model should also be able to fulfil the budget of bomb-produced radiocarbon and $^{13}C$. In general, the budget of the two carbon isotopes serves as an additional constraint of carbon cycle models. A second major aim of our previous grant was to use the isotopic budgets to constrain our carbon cycle model.

The global budget of bomb-produced radiocarbon appears not to be balanced [*Hesshaimer et al.*,1994], [*Broecker and Peng*, 1994, *Joos*, 1994]. After 1963, the global amount of bomb-radiocarbon should have remained approximately constant as production was small. Except for the biosphere, global observations exist for the troposphere, the stratosphere, and the ocean. The tropospheric concentration was monitored continuously since the onset of the bomb-tests. Stratospheric data exist until 1969 and for 1989 onwards. We derive the oceanic uptake by using the HILDA model, calibrated to match the observed bomb-radiocarbon distribution at time of GEOSECS. To estimate the uptake of the remaining reservoir, we use the 4-box biosphere developed by Siegenthaler and Oeschger [1987]. By comparing the changes in the different reservoirs and production by bombs, an imbalance of the order of 10% of the global bomb-radiocarbon inventory is found.

Hesshaimer et al. [1994] concluded that the bomb-radiocarbon ocean inventory estimate of Broecker and co-workers is too large and that therefore estimates of the oceanic $CO_2$ uptake should be revised downward by about 25 %. This presents a major challenge to carbon cycle modeling work. To assess this problem, we extended the work of Hesshaimer by considering the budget of $^{13}C$ as well.

Using least squares, a set of optimized values of the parameters of the HILDA model and the 4-box biosphere was determined to satisfy simultaneously the constraints of a closed budget for anthropogenic $CO_2$, $^{13}C$, bomb-produced radiocarbon, as well as the oceanic observations of natural and bomb-radiocarbon within the error limits of observations. Results show

that the oceanic uptake of anthropogenic carbon and bomb-radiocarbon are only slightly changed when using the set of optimized instead of standard parameters. However, simultaneous closure of the $^{13}C$ and the bomb-produced radiocarbon budget cannot be achieved exactly with this model. The less relative weight is given in the optimization procedure on the $^{13}C$-budget, the better the bomb-radiocarbon budget can be fulfilled and vice versa.

In a next step, we replaced the 4-box biosphere used to simulate the dilution of an isotopic perturbation by the land biota by a more elaborate biosphere model. This model includes additional compartments representing leaves and fine root, sap wood, heart wood, leaf litter, woody litter, active soil and slow soil. Consequently, the dynamics of organic matter overturning is allowed to include a wider range of different time scales. Despite the increased number of parameters to be optimized, we did not find a substantially better solution than with the 4 box land biota model. The global inventory of bomb-produced radiocarbon remains in imbalance (about 10%), and simulated atmospheric $^{13}C$ levels deviate from observations by about 0.1 $^{0}/_{00}$ in 1980.

From this we conclude (1) that a lowering of the oceanic bomb-radiocarbon inventory estimate by Broecker et al. conflicts with the budget of $^{13}C$; (2) the major uncertainties in the $^{14}C$ budget arise from uncertainties in the stratospheric observations and in the yield factor, i.e. the amount of radiocarbon produced per bomb explosive power, - a release of classified stratospheric measurements could potentially clarify these aspects; (3) that the HILDA model includes the important time scales of carbon exchange between land, atmosphere and ocean reasonably accurately; (4) there is no need to revise our previous model estimates of anthropogenic $CO_2$ uptake.

### 3.2.4 Estimating net fertilization fluxes into the land biota

We have used the HILDA model to analyze the high precision measurements of atmospheric $^{13}C$ and $CO_2$ , provided by R. Francey, CSIRO Australia, and M. Leuenberger, a research associate at the Physics Institute in Bern. These data have been obtained by a recent analysis of an Antarctic ice core and cover roughly the period of the last 300 years [*Etheridge et al.*, 1996]. The $^{13}C$ data are still preliminary and not yet released for publication by the Australian group. When finalized, the data will allow us to reconstruct the history of the oceanic and biospheric carbon uptake during the last two centuries.

We have updated earlier deconvolution simulations [*Siegenthaler and Oeschger*, 1987], [*Sarmiento et al.*,1992], [*Siegenthaler and Joos*, 1992] using the most recent high-precision $CO_2$ measurements obtained from firn and ice at a high accumulation site at Law Dome Antarctica combined with direct atmospheric measurements from Mauna Loa and Southpole [*Bruno and Joos*, 1996]. For the first time, we have estimated the uncertainty of the deduced terrestrial sink term due to uncertainties in atmospheric $CO_2$ data by using Monte Carlo statistics. Further, we compared results obtained by using the Law Dome data with those from the well-known Siple ice core $CO_2$ data [*Neftel et al.*, 1985]. To assess uncertainties in ocean uptake, we use four different ocean models: two box-type models, i.e. the box-diffusion model [*Oeschger et al.*, 1975] and the HILDA model [*Siegenthaler and Joos*, 1992], a 2.5-D model [*Stocker et al.*, 1994], and a 3-D model [*Sarmiento et al.*, 1992]. The mod-

els are used in their mixed-layer pulse substitute representations [*Joos et al.*, 1996] to save computing time and to allow us to run the model several thousand times for the Monte Carlo simulations.

Results of this deconvolution and our preliminary results for the $\delta^{13}C$ analysis (Fig. 4) show that the atmospheric $CO_2$ and $^{13}C$ data are consistent if one assumes that the biosphere acted as a source of about 0.5-1 GtC/yr between 1800 and 1930, almost balanced between 1920 and 1965 and as a carbon sink afterwards. Until 1930, these results based on the $CO_2$ and isotope data agree with independent estimates of carbon fluxes due to deforestation and land use change from statistics. After 1930, our analysis indicates a small net biospheric sink, whereas estimates of deforestation fluxes based on statistics give a substantial carbon release into the atmosphere [*Houghton et al.*, 1994]. This suggests that a terrestrial sink compensates for carbon emissions due to deforestation.

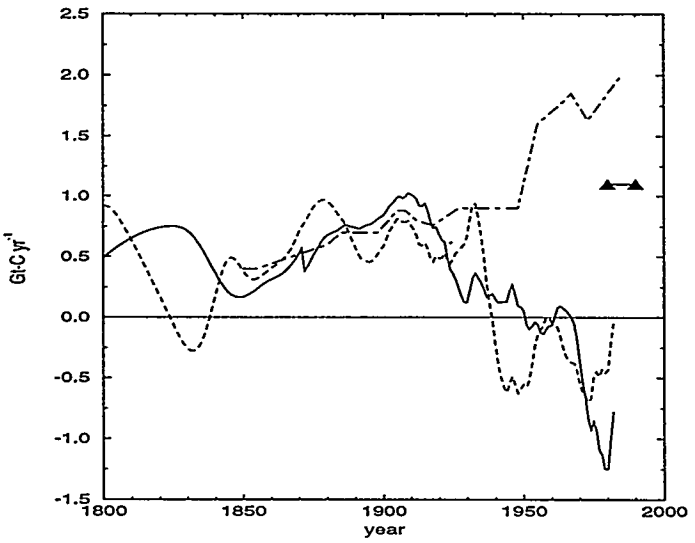


Figure 4: *Net carbon fluxes between atmosphere and biosphere as obtained by a single deconvolution of the atmospheric $CO_2$ record (dashed line; [Bruno and Joos, 1996]) and by a double deconvolution of the $CO_2$ and $^{13}C$ record (solid line; preliminary results); estimated carbon release into the atmosphere due to deforestation and land use change from statistics (dash-dotted line [Houghton, 1993]); estimated carbon emission during the last decade due to deforestation and land use change taking into account forest regrowth in northern latitudes (filled triangle.[Houghton et al., 1994])*

### 3.2.5 Ocean carbon transport in a box-diffusion vs. a general circulation model

A major hypothesis in many anthropogenic $CO_2$ studies is that radiocarbon observations are well suited to calibrate or validate ocean models of anthropogenic $CO_2$ uptake. Despite its widespread use, this hypothesis remains largely untested. Results from box-diffusion type models are included in present estimates of the budget of anthropogenic $CO_2$ (e.g. [*Houghton et al.*, 1996]. Though the eddy diffusion concept is widely used in Earth system

science only a few papers investigate whether the use of this parameterization is appropriate or not.

We compared vertical transports of temperature, anthropogenic $CO_2$, natural radiocarbon ($^{14}C$), and bomb $^{14}C$ in a global box-diffusion model (B-D) and a three-dimensional ocean general circulation model from GFDL. Our main objectives were: (1), to test the eddy diffusion parameterization of large-scale vertical transport in ocean box models; and (2), to assess the utility of bomb-produced and natural $^{14}C$ observations to validate ocean models of anthropogenic $CO_2$ uptake [*Joos et al.*, 1996].

From the 3-D model's distributions and fluxes of natural $^{14}C$, bomb $^{14}C$, and anthropogenic $CO_2$, we calculated apparent diffusivities, $K_z^{ap}(z)$, vertically over the global ocean that range mostly between $1 \times 10^{-4}$ and $2 \times 10^{-4}$ $m^{-2}$ $s^{-1}$ . These $K_z^{ap}(z)$ agree quantitatively with diffusivities found by fitting B-D models to observed distributions of natural and bomb $^{14}C$. We then used these sets of $K_z^{ap}(z)$ in different runs of a global B-D model. Results from all B-D models runs matched to within 13% those from the 3-D model for global uptake of anthropogenic $CO_2$ and bomb-$^{14}C$ penetration depth.

Although $K_z^{ap}(z)$ from 3-D simulations for bomb $^{14}C$ varied with time, those from 3-D runs for anthropogenic $CO_2$ were essentially constant. Yet we found nearly the same results with the B-D model when $K_z^{ap}(z)$ from 3-D bomb $^{14}C$ simulations were approximated as time invariant. The best agreement (within 3% ) between 3-D and B-D model was found when applying $K_z^{ap}(z)$ derived from bomb-$^{14}C$ in the surface and from natural $^{14}C$ in the deep. We found it appropriate to study global oceanic uptake of anthropogenic $CO_2$ with B-D model and to validate anthropogenic carbon uptake models using natural and bomb $^{14}C$ observations.

For bomb $^{14}C$, convective transport was most important during 1955-1964 while atmospheric levels were rising; afterwards atmospheric levels drop and advective overturning dominates. Thus bomb-$^{14}C$ seems less than ideal to validate the convective scheme of general circulation models.

### 3.2.6 Reconstruction of anthropogenic $CO_2$ in the North Atlantic

The independent estimate of oceanic $CO_2$ uptake based on direct observations provides an additional powerful constrain on the oceanic $CO_2$ uptake and helps us to validate ocean models.

We have developed an improved method for the separation of the anthropogenic $CO_2$ signal from the large natural background variability of dissolved inorganic carbon ($C$) in the ocean [*Gruber et al.*, 1996]. This technique employs a new conservative carbon tracer $\Delta C^*$, which reflects the uptake of anthropogenic $CO_2$ and the air-sea disequilibrium when a water parcel lost contact with the atmosphere. The air-sea disequilibrium component can be discriminated from the anthropogenic signal using either information about the water age or the distribution of $\Delta C^*$ in regions not affected by the anthropogenic transient. This technique has been applied to data from the North Atlantic sampled during the TTO NAS and TAS cruises in 1981-1983. The highest anthropogenic $CO_2$ concentrations and specific inventories (inventory per $m^2$) are found in the subtropical convergence zone. In the North

Atlantic, anthropogenic $CO_2$ has already invaded deeply into the interior of the ocean, north of 50°N it has even reached the bottom. Only waters below 3000 m and south of 30°N are not yet affected. We estimate an anthropogenic $CO_2$ inventory of 20 ± 4 GT C in the North Atlantic between 10°N and 80°N. The performance of two ocean models with regard to their prediction of ocean uptake of anthropogenic $CO_2$ has been investigated. These models include the 2.5D ocean circulation model of *Stocker et al.* [1994] and the 3D ocean biogeochemistry OGCM of *Sarmiento et al.* [1995]. Both models are in good agreement with the observed total anthropogenic $CO_2$ inventory (18.7 GT C and 18.4 GT C, respectively). Important differences exist on a more regional scale, associated with known deficiences of the models.

### 3.2.7 Review Articles on the Anthropogenic $CO_2$ Perturbation

F. Joos and J. Sarmiento (1995) wrote a review article summarizing present knowledge about the global carbon cycle and its perturbation by man. The article was requested by "Physikalische Blätter"; that is the journal of the German Physical Society and as such comparable to "Physics Today". F. Joos wrote a similar review article for Europhysics News [*Joos*, 1996], i.e. the journal of the European Physical Society.

## 3.3 Projects Related to This Proposal

### 3.3.1 Sensitivity of Local Air-Sea Carbon Fluxes on Carbon Chemistry

The fugacity ($fCO_2$) of carbon dioxide ($CO_2$) in surface seawater is one factor that determines the carbon flux from atmosphere to ocean. Our main purpose was to investigate the uncertainties of $fCO_2$ and to clarify how accurately $CO_2$ air-sea fluxes can presently be determined [*Fink and Murnane*, 1996].

We focused on two methods of calculating $fCO_2$. The first method is based on measurements of seawater concentrations, in the second method we apply mole fraction measurements, combined with a temperature correction in order to account for the discrepancy between laboratory temperature and SST. We use "full chemistry" calculations, i.e. the $CO_2$ solubility, all dissociation constants of carbonic, boric, silic and phosphoric acids and of water as well as total alkalinity (TALK) and total concentrations of carbon (TC), borate (TB), phosphate and silicate.

An uncertainty in $fCO_2$ up to 20 ppm was found which is substantially larger than today's annual mean difference between atmosphere and sea surface of about 8 ppm. The largest contributions of Method 1 are due to errors in the total concentrations (the squared relative contribution to total error is on the average about 60 %, mainly due TALK, TB, and TC) and the dissociation constants (30 %, mainly due to carbonic acid).

The error contributions of Method 2 varies, depending on the applied laboratory temperatures: The largest uncertainties are due to dissociation constants (0 % to 50 %) and SST (25 % to 95 %). A comparison between our full chemistry calculations and an exponential temperature correction method [*Takahashi et al.*, 1993] shows remarkable systematic deviations up to 30 ppm.

For the error-calculation of air-sea fluxes, in addition to the error in $fCO_2$, uncertainties in the transfer coefficient, the "skin effect" and other quantities are included. Though an estimated 20 % error in the transfer coefficient is assumed, the sum of the other error sources is significant and can be the leading term in the flux error in some regions of the ocean. In the Atlantic (GEOSECS data), for example, the error of the transfer coefficient is 0.13 GT-C/yr, the other uncertainties contribute 0.17 Gt-C/yr to the total error of 0.22 Gt-C/yr (square root of the sum of the two squared errors). This total 2-$\sigma$ error depends on the used method to determine $fCO_2$ of oceanic surface water and can be reduced at most to 0.16 Gt-C/yr. The deviation between full chemistry calculation and exponential temperature correction are up to 1.1 Gt-C/yr.

Mole fraction measurements can lead to much more accurate results than measurement of seawater concentrations. If the mole fraction is determined at temperatures close to SST, the large systematic error vanishes and the statistical error can be substantially reduced. But even for the most accurate $fCO_2$ determination, the errors of $CO_2$ flux are still large and it seems difficult to give accurate estimates, e.g. of the anthropogenic C-uptake, based solely on $fCO_2$ determinations.

### 3.3.2 Calculation for the Intergovernmental Panel on Climate Change

The 'Bern carbon cycle model', i.e. HILDA model coupled to a 4-box terrestrial biosphere component was chosen by the Intergovernemental Panel on Climate Change, Working Group I, as reference model for the scenario calculations presented in various reports [*Houghton et al.*, 1994, *Houghton et al.*, 1996, *Enting et al.*, 1994]. This Bern model has been developed under funding from DOE. We have performed all the scenario calculations proposed for the IPCC 1994 report and about 50 additional simulations linking anthropogenic emissions and atmospheric $CO_2$ concentration for the IPCC 1995 update chapter on radiative forcing. In the 'Bern carbon cycle model' the magnitude of the terrestrial carbon sink, e.g. due to plant fertilization by elevated $CO_2$ levels or nutrient supply, was tuned in order to balance the budget of anthropogenic $CO_2$ for the last decade. Therefore, this biospheric sink term depends strongly on the assumption about land use changes and deforestation, the most uncertain factor of anthropogenic emissions. Based on best estimates of land use changes, deforestation and forest regrowth, a biospheric net emission due to these processes of 1.1GtC/yr was diagnosed for the last decade. Sensitivity of the model results on this prescribed 'deforestation' flux have been investigated for the stabilization scenarios (S350-S750) and the 1990 scenarios (is92a-f) (Houghton et al., 1990+1992). The higher the assumed deforestation flux the more carbon must be taken up by the biosphere in order to balance the budget during the last decade. For scenario S550 (stabilization of future atmospheric $CO_2$ at 550ppm), we find that the cumulative biospheric sink term for the period 1990–2100 varies between 85 and 320 GtC for assumed average deforestation fluxes between 0.4 and 1.8 GtC/yr for the 80's.

U. Siegenthaler and F. Joos were invited lead authors to the chapters on the global carbon cycle for the 1990, 1994, and 1995 report of IPCC. F. Joos serves as a lead author for two technical paper in preparation.

## 3.4 Graduate Student Supported (1993–96)

*M. Bruno* started his Ph.D. thesis at the University of Bern in October 1993. He will complete his thesis by the end of this year. Important results of his thesis are now being published [*Joos et al.*, 1996, *Bruno and Joos*, 1996] and have been presented at international conferences.

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