ORNL/FTR--3847

DE91 005985

COVER SHEET
FOR TRIP REPORTS SUBMITTED TO THE OFFICE OF ENERGY RESEARCH

Destination(s) and Dates for Which Trip Report Being Submitted: Princeton, New Jersey - June 1 - July 22
Friday Harbor, WA. - July 22 - August 26
Princeton, New Jersey - August 26 - October 1
Princeton, New Jersey - October 28 - December 20

Name of Traveler: L. Fortunat Joos

Joint Trip Report ☐ Yes
☒ No

If so, Name of Other Traveler(s): _____

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ORNL

FOREIGN TRIP REPORT

ORNL/FTR-3847

DATE: December 20, 1990

SUBJECT: Report of Foreign Travel of L. Fortunat Joos, Physics Institute, University of Bern, Switzerland

TO: Alvin W. Trivelpiece

FROM: L. Fortunat Joos

PURPOSE: To collaborate with principal investigators at Princeton University on anthropogenic CO_2 experiments that are required for the work specified in the subcontract.

SITES VISITED:

6/1-7/22/90, 8/26-10/1/90, 10/28-12/20/90	Princeton University	Princeton, New Jersey	J. L. Sarmiento
7/22-8/26/90	University of Washington	Friday Harbor, Washington	J. L. Sarmiento

ABSTRACT: The traveler collaborated with Dr. J. L. Sarmiento of the Program in Atmospheric Sciences, Princeton University, and Dr. U. Siegenthaler of the University of Bern in box-model studies of the potential enhancement of oceanic CO_2 uptake by fertilizing the southern ocean with iron. As a result of this collaboration, a letter describing the results was submitted to the journal *Nature*. Sensitivity studies were carried out to gain a better understanding of the processes involved for a hypothetical iron fertilization of the ocean. An article that describes this work has been submitted to the journal *Global Biogeochemical Cycles*. The traveler and U. Siegenthaler are preparing a journal article describing a box model of the global carbon cycle that is an extension of the one-dimensional box-diffusion model. The traveler attended Oceanography 590b at the University of Washington in Friday Harbor. While at Friday Harbor, he started to collaborate with Drs. M. Warner, R. Gammon, and J. Bullister, all from the University of Washington, Seattle, to calibrate the global carbon cycle model with chlorofluorocarbon (CFC)-11 and CFC-12. The traveler started collaboration with Drs. J. C. Orr and J. L. Sarmiento to calculate apparent eddy diffusivities from the Princeton three-dimensional ocean model. The work is conducted by the University of Bern, Switzerland (the traveler is principal investigator), for a U.S. Department of Energy program managed by Oak Ridge National Laboratory.

REPORT OF ACTIVITIES

The purpose of this trip was to collaborate with Dr. J. L. Sarmiento and his co-workers [Program in Atmospheric and Oceanic Sciences (PAOS), Princeton University] on modeling the role of the ocean in the global carbon cycle, especially the uptake of anthropogenic CO_2, by using a box model developed at the University of Bern. Two projects have been completed, and two articles (by the traveler, J. L. Sarmiento, and U. Siegenthaler) describing the results has been submitted to journals: (1) a letter to *Nature* describing the results of a hypothetical iron fertilization of the southern ocean ("Potential Enhancement of Oceanic CO_2 Uptake by Iron Fertilization of the Southern Ocean" and (2) an article for submission to *Global Biogeochemical Cycles* describing the results of sensitivity studies for the effect of iron fertilization on atmospheric CO_2 ("Possible Effects of Iron Fertilization in the Southern Ocean on Atmospheric CO_2 Concentration").

A first project was to write a journal article describing a High-Latitude Exchange/Interior Diffusion-Advection (HILDA) model of the global ocean-atmosphere system. This box-type model, first proposed by Shaffer and Sarmiento, was extensively calibrated by using different stationary and transient tracers [natural and bomb-produced ^{14}C, temperature, and chlorofluorocarbons (CFCs)]. It is used for simulating the anthropogenic perturbations of CO_2, as well as of its isotopic composition (^{13}C, ^{14}C). The HILDA model is an extension of the box-diffusion and outcrop-diffusion models developed earlier at the University of Bern. The HILDA model consists of a low-latitude surface-water box underlain by an advective-diffusive low-latitude interior reservoir and a high-latitude surface-water box underlain by a well-mixed high-latitude deep box.

The HILDA model has the box models' advantage of simplicity but allows one to study the important effects of the fast transport in high latitudes. Two findings are particularly worth mentioning. First, the distributions of natural and bomb-produced ^{14}C in the ocean (which are governed by different time scales) can be reproduced only with depth-dependent eddy-diffusivity coefficients, with higher values at the top. Analyses of tracer transport in the Princeton three-dimensional ocean model show that this can be explained by more vigorous vertical transport near the surface than in the deep sea, attributable to wind-driven as well as thermohaline circulation. Second, temperature cannot be simulated with the coarse horizontal resolution in the HILDA model and with the transport parameters derived from ^{14}C: the deep model ocean is too warm. The explanation is the fact that the source region from where the bulk of the thermocline is ventilated is situated in mid-latitude and is colder than the average sea surface temperature for the low-latitudes and the mid-latitudes, which are all grouped in one surface box in the model. The surface distributions of ^{14}C and the anthropogenic CO_2 perturbation in the ocean are, in contrast, much more uniform between 50°N and 50°S than temperature (i.e., ^{14}C and CO_2 perturbations are not aligned parallel to isothermal surfaces). The average ocean uptake for 1980-1989 calculated by the standard version of the HILDA model is about 2.2 gigatons of carbon per year.

A first draft of the paper describing the HILDA model and our results has been written. We plan to submit the manuscript to *Tellus* for publication when the paper is completed.

The traveler attended the summer course, Oceanography 590b, in Friday Harbor. The course covered fluid dynamics as well as geochemistry and was taught by P. Rhines and J. L. Sarmiento, as well as other guest lecturers. Besides attending lectures, each student worked on projects. With the help of Dr. M. Warner, CFC-11 and CFC-12 were included in the HILDA model. Drs. M. Warner and R. Gammon, visitors at this summer course, provided CFC-11 and CFC-12 data from the Atlantic and Pacific oceans. From these data, a CFC-11 inventory of 1950 $\pm$550 nmol/m^{-2} in 1984 was estimated for the ocean south of 45°S, an area which corresponds to the high-latitude part of the HILDA model. A simulation with HILDA model shows that the model parameters derived from calibration with natural and bomb radiocarbon can be used to reproduce the CFC data quite well. Especially important are the transport parameters in the high-latitude region. These are not well defined by the radiocarbon data, and they strongly affect the model response for a hypothetical iron fertilization of the high-latitude ocean. The predicted model inventory for the high-latitude ocean in 1984 was 1976 nmol/m^{-2}, in close agreement with the observed inventory. Thus, the high-latitude transport parameters derived from radiocarbon data are supported by the CFC results.

The HILDA model is able to fit the observed CFC-11 and CFC-12 inventory in the high latitudes, but it predicts a bomb radiocarbon inventory too large compared with that of the observation. This discrepancy might be due to inaccurate estimates of the CFCs or the radiocarbon inventory. Data sets of tracer distribution in the high-latitude ocean are still scarce. For the ocean south of 45°S, only 17 profiles are available to estimate bomb radiocarbon inventories, whereas the previous estimation of CFC-11 inventory is based on more than 100 profiles. The bomb radiocarbon inventory given by Broecker and others may be too low in the high latitudes because the way in which these researchers determined the inventory led them to miss bomb ^{14}C that penetrated all the way down in the water column. Since CFC measurements are easier to interpret, have greater precision, and are more frequent in the southern ocean, the traveler tends to trust the CFC data better. However, the discrepancy between CFC and bomb radiocarbon measurements will be studied further.

First results of this summer project in Friday Harbor have been written up and will be distributed to the participants of the course.

The main project during the traveler's tenure in Princeton was to study the potential enhancement of oceanic CO_2 uptake by iron fertilization. This project was done in collaboration with Drs. J. L. Sarmiento and U. Siegenthaler by using the HILDA model. Martin and others have found evidence that a limited supply of iron may explain why the productivity of marine biota is not larger in oceanic regions where nutrients (phosphate and nitrate) are abundant. This has led to the suggestion that fertilizing the oceans with iron might be a way to mitigate the anthropogenic increase of atmospheric CO_2 by increasing the biological uptake of carbon. An increased biological uptake would decrease surface ocean CO_2 partial pressures. Hence the ocean would take up more CO_2 from the atmosphere.

We have found that the three most important factors controlling the response of atmospheric CO_2 to an enhanced carbon uptake resulting from iron fertilization are the following:

1. The reduction in average ΣCO_2 per unit area that occurs when fertilization is initiated. We take the supply of phosphate as a reasonable guide to calculate the maximum potential biological uptake of carbon (i.e., we assume, for estimating the upper limit of the effect on CO_2, that phosphate is the only limiting factor besides iron).

2. The area over which the fertilization occurs. Since iron fertilization can have a significant effect only if sufficient phosphate is available, we have assumed fertilization to be carried out in those regions of the southern ocean where the surface phosphate concentration exceeds 1 $mmol/m^{-3}$; this corresponds to 16% of the world's ocean surface. Alternatively, we considered an area of 9.7%.

3. The reduction in CO_2 partial pressure resulting from a given decrease of ΣCO_2. The reduction is governed by carbonate chemical equilibria. The change in partial pressure is sensitive to the actual atmospheric CO_2 concentration because of the nonlinearity of the chemical system.

Our model estimates suggest that an upper limit to the possible drawdown of atmospheric CO_2 that could be achieved by iron fertilization of phosphate-rich waters of the southern ocean is in the range of 34 to 60 ppm over 50 years and 58 to 107 ppm over 100 years. This would require continuous fertilization, year after year; if the fertilization were terminated at any time, the trapped CO_2 would return to the atmosphere. These results have to be compared with the CO_2 increase estimated to occur without iron input to the oceans. While the reduction due to enhanced marine productivity is noticeable, a further significant increase in atmospheric concentration could not be stopped by this measure. For a business-as-usual scenario, implying an approximately linear increase of emissions until 2100, an atmospheric concentration of 773 ppm is calculated for 2090 without iron fertilization and 666 ppm with iron fertilization.

The previously mentioned letter to *Nature* (authored by the traveler, J. L. Sarmiento, and U. Siegenthaler) describes the results of this project. To gain a better understanding of the processes that govern the magnitude and rate of an atmospheric CO_2 reduction due to iron fertilization, we carried out a number of sensitivity studies. The main results are as follows:

1. We estimated the error of the predicted reduction in atmospheric CO_2 due to uncertainties in the transport parameters. Uncertainties in the transport parameters are estimated from the model results for CFC-11 and radiocarbon. The sensitivity of iron fertilization to each parameter was calculated, varying one parameter at a time. The model is most sensitive to the transport parameters in high latitudes (i.e., gas exchange and surface-to-deep exchange). We get a possible error of the CO_2 reduction due to uncertainties in the transport parameters in the range of -55% to +37%.

2. During the winter months there is no light in the high latitudes, and biological productivity is close to zero. If iron-stimulated biological productivity is halted during the six winter months, the additional oceanic CO_2 uptake is reduced by 18% compared with the standard case. Light limitation during the summer months may also be important.

3. Part of the additional particle flux due to iron fertilization might be buried in sediments, or part of the additional new production might be transformed to dissolved organic matter, with a breakdown rate of 1/200 per year, instead of sinking to the deep ocean and remineralizing in 3-30 days. Furthermore, carbon and phosphate may be mineralized at different rates in the water column and sediments. We found, in various scenarios, that particle burial or transformation of new production in dissolved organic matter has a very small effect on the reduction of atmospheric CO_2 due to iron fertilization.

4. Besides carbon and phosphate, sinking particles transport alkalinity. Since the equilibrium partial pressure of the surface water, which determines the air-sea flux, is a function not only of ΣCO_2 but also of alkalinity, alkalinity transport affects the results for iron fertilization. However, alkalinity transport is relatively unimportant in high latitudes. We found that changes in surface alkalinity may affect the reduction in atmospheric CO_2 due to fertilization by 110%.

The previously mentioned article (by the traveler, U. Siegenthaler, and J. L. Sarmiento) describing the results of the sensitivity studies has been submitted to *Global Biogeochemical Cycles*.

The two previous studies are intended to give an idea of the upper possible limit of the CO_2 reduction due to iron fertilization. It is based on the hypothesis that marine productivity in the southern ocean is limited solely by iron. We did not take into account any ecological effects of iron fertilization, which might be serious and which seem virtually impossible to assess presently, considering the very limited knowledge of the factors regulating marine ecosystems. This alone should inhibit any serious plans for a large-scale fertilization of oceanic regions with iron. Our calculations further indicate that the effort to achieve a significant effect on CO_2 would be enormous and would have to be continued for an indefinite period of time. Otherwise, the sequestered CO_2 would return to the atmosphere.

The traveler started collaboration with Drs. J. C. Orr and J. L. Sarmiento, PAOS, to calculate apparent eddy-diffusivities K_{app} from the Princeton three-dimensional ocean model. Calculation of K_{app} will allow better comparison of three-dimensional model results and results of box models, in which tracer fluxes are parameterized by a flux-gradient relationship. Furthermore, apparent eddy diffusivities can be used as a diagnostic tool for analyzing the three-dimensional model results. The first part of the calculations of K_{app}, the zonal averaging of the three-dimensional model results, has been done; therefore, the traveler will be able to complete the project in Bern. The traveler plans to publish the results.

APPENDIX A

ITINERARY

6/1-7/22	Princeton, New Jersey
7/22-8/26	Friday Harbor, Washington
8/26-10/1	Princeton, New Jersey
10/1-10/28	Vacation
10/28-12/20	Princeton, New Jersey
12/20	Travel to Bern, Switzerland

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