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 - Sept. 23-24
Buffalo, New York - Sept. 25-28
Palisades, New York, Oct. 4-6
Princeton, New York, Oct. 14-24

Name of Traveler: Ulrich C. Siegenthaler

Joint Trip Report ☐ Yes
☒ No

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

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FOREIGN TRIP REPORT

ORNL/FTR-3811

DATE: November 6, 1990

SUBJECT: Report of Foreign Travel of Ulrich Siegenthaler, Privatdozent, Physics Institute

TO: Alvin W. Trivelpiece

FROM: Ulrich Siegenthaler

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

SITES VISITED:

09/23-24/1990	Princeton University	Princeton, New Jersey	J. L. Sarmiento
09/25-28/1990	State University of New York	Buffalo, New York	C. C. Langway
10/04-07/1990	Lamont-Doherty Geological Observatory	Palisades, New York	J. L. Sarmiento
10/14-24/90	Princeton University	Princeton, New Jersey	J. L. Sarmiento

ABSTRACT: The traveler collaborated with Drs. J. L. Sarmiento and J. C. Orr of the Program in Atmospheric Sciences at Princeton University to finish the article "A Perturbation Simulation of CO_2 Uptake in an Ocean Circulation Model," which has been submitted to the *Journal of Geophysical Research* for publication. With F. Joos, a graduate student from the University of Bern, the traveler started writing 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 further collaborated with F. Joos and Dr. J. L. Sarmiento on modeling the potential enhancement of oceanic CO_2 uptake by fertilizing the southern ocean with iron. A letter describing the results is currently being written for the journal *Nature*.

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.

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BACKGROUND INFORMATION

The purpose of this trip was to enable the traveler to collaborate with other researchers on modeling the role of the ocean in the global carbon cycle, especially the uptake of anthropogenic CO_2. For this purpose, a three-dimensional ocean carbon cycle model has been developed at Princeton University, while a box model was developed simultaneously at the University of Bern.

The first project, which was completed during the traveler's visit to Princeton, was to finish an article presenting the results of an initial series of three-dimensional model experiments on the ocean's uptake of anthropogenic CO_2. The article, jointly authored by J. L. Sarmiento, J. C. Orr, and the traveler ("A Perturbation Simulation of CO_2 Uptake in an Ocean General Circulation Model"), has been submitted for publication to the *Journal of Geophysical Research*. The uptake of anthropogenic CO_2 by the ocean is simulated by using a perturbation approach in three-dimensional global general circulation model. Atmospheric CO_2 partial pressure is estimated for the period 1750 to 1990 with the use of the combined Siple ice core and Mauna Loa records. For the period 1980 to 1989, the average flux of CO_2 into the ocean is 1 gigaton of carbon per year. The bomb radiocarbon simulation of Toggweiler and others shows that the exchange between surface and deep ocean in this model is too sluggish, suggesting that the CO_2 uptake calculated by the model is too low. The observed atmospheric increase from 1980 to 1989 is 3.2 gigatons of carbon per year, for a combined atmosphere-ocean total of 5.1 gigatons of carbon per year. This latter value is comparable to the estimated fossil CO_2 production of 5.4 gigatons of carbon per year, implying that other sources and sinks (such as from deforestation, enhanced growth of land biota, and changes in the ocean carbon cycle) must be approximately in balance. The sensitivity of the uptake to the gas exchange rate is small: a 100% increase in the gas exchange rate gives only a 9.2% increase in cumulative oceanic uptake. Details of the penetration into different oceanic regions are also discussed in the article. The traveler's research suggests that the conclusion of a recent paper by Tans, Fung, and Takahashi is erroneous. Global oceanic uptake is probably ≥ 2 gigatons of carbon per year, not 1 gigaton of carbon per year as these other scientists conclude.

A second project during the traveler's visit to Princeton 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 (such as natural and bomb-produced ^{14}C and temperature). The model is intended for simulating the anthropogenic perturbations of CO_2 as well as perturbations 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. It consists of a low-latitude and high-latitude surface-water box underlain by an advective-diffusive low-latitude interior reservoir and a well-mixed high-latitude deep box.

This model structure, while still having the box models' advantage of simplicity, permits the study of effects of the relatively fast transport in high latitudes, a factor important in the distribution of oceanic properties. Two findings are particularly worth mentioning. First, the distribution of both natural and bomb-produced ^{14}C in the ocean (governed by different time scales) requires that eddy diffusivity is assumed to be depth dependent, producing higher values of ^{14}C at the top. Analyses of trace transport in the Princeton three-dimensional ocean model show that this phenomenon 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 in a model with such a coarse horizontal resolution; the deep model ocean is too warm. The reason is that the source region from which the bulk of the thermocline is ventilated is situated in the middle latitudes and is colder than the average near-surface temperature of the model. The surface distributions of ^{14}C and the anthropogenic CO_2 perturbation in the ocean are, in contrast, much more uniform (e.g, between 50° N and 50° S) than temperature. The average ocean uptake for 1980 to 1989 calculated by the standard version of the HILDA model is about 2.2 gigatons of carbon per year, slightly higher than in the three-dimensional model mentioned previously. A first draft of the paper describing the HILDA model has been written. When completed, the manuscript will be submitted to *Tellus* for publication.

As a third project, the traveler (along with F. Joos and J. Sarmiento) studied the potential enhancement of oceanic CO_2 uptake by iron fertilization with the use of the HILDA model. Other researchers have found that a limited supply of iron may explain why the productivity of marine biota is not greater in oceanic regions where nutrient (phosphate nitrate) and light are abundant. This finding has led to the suggestion that fertilizing the oceans with iron might be a way to increase the biological uptake of carbon, thus decreasing surface-ocean CO_2 partial pressures and increasing the uptake of CO_2 from the atmosphere in order to mitigate the anthropogenic increase of atmospheric CO_2.

The traveler and his associates have identified three important factors controlling the response of atmospheric CO_2 in an enhanced carbon uptake resulting from iron fertilization. First is the reduction in average $\sum CO_2$ per unit area that occurs when fertilization is initiated. The supply of phosphate is used as a reasonable guide to the maximum potential biological uptake of carbon (i.e., for estimating the upper limit of the effect on CO_2, phosphate is assumed to be the only limiting factor besides iron). Second is the area over which the fertilization occurs. Since iron fertilization can have a significant effect only if sufficient phosphate is available, the traveler and his associates 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 ocean's surface. (Alternatively, the traveler considered an area of 9.7%, as other researchers have done.) The third factor is the reduction in CO_2 partial pressure resulting from a given decrease of $\sum CO_2$; this is governed by carbonate chemical equilibria and is sensitive to the actual atmospheric CO_2 concentration because of the nonlinearity of the chemical system.

The model estimates of the traveler and his associates suggest that an upper level 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 100 ppm over 100 years. Maintaining this level would require continuous iron fertilization year after year; if the fertilization were terminated at any time, the trapped CO_2 would escape back into the atmosphere. These results have to be compared with the CO_2 increase estimated to occur without iron input to the ocean. Although the reduction due to the enhanced marine productivity is noticeable, a further significant increase in atmospheric concentration of CO_2 could not be stopped by this measure. For a business-as-usual scenario, implying an approximately linear increase of emissions until 2100, atmospheric concentrations in 2090 are estimated to be 790 ppm without iron fertilization and 690 ppm with iron fertilization.

This study is intended to give an idea of the upper possible limit of the CO_2 reduction due to iron fertilization. It is based on the not-yet-proved hypothesis that marine productivity in the southern ocean is limited solely by iron. The study does not take into account the potentially significant effects on the marine ecology, because such effects cannot be assessed presently. This factor alone should prohibit the development of serious plans for large-scale fertilization of oceanic regions with iron. The traveler's calculations further indicate that efforts required to achieve a significant effect on CO_2 would be extensive and would have to be continued for an indefinite period of time.

PARTICIPATION BY TRAVELER

The traveler was invited to conduct seminars at three research institutions. At the Department of Geology, State University of New York at Buffalo, he presented the seminar "Information on Climate and the Global Carbon Cycle from Ice Cores and Lake Sediments." At Buffalo, the traveler also discussed (with Dr. C. C. Langway, Professor, Department of Geology) plans to measure CO_2 concentrations and $^{13}C/^{12}C$ ratios by using old polar ice cores. At the Lamont-Doherty Geological Observatory, Palisades, New York, the traveler gave a colloquium talk entitled "Atmospheric ^{14}C Variations 10,000-14,000 years B.P. and Atmospheric CO_2 and ^{13}C Since 1750—Ice Core Data and Modeling". At the Geophysics Fluid Dynamics Laboratory in Princeton, New Jersey, the traveler presented a seminar talk entitled "Atmospheric CO_2 AD 1000 to AD 2100."

APPENDIX A

ITINERARY

9/23-24	Princeton, New Jersey
9/25-28	Buffalo, New York
9/28-10/3	Vacation
10/4-7	Palisades, New York
10/8-13	Vacation
10/14-24	Princeton, New York
10/24-25	Travel to Bern, Switzerland

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