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ORNL
FOREIGN TRIP REPORT
ORNL/FTR-3373

DATE: September 1, 1989

SUBJECT: Report of Foreign Research Assignment by T.-H. Peng, Research Staff, Geosciences Section, Environmental Sciences Division

TO: Alvin W. Trivelpiece

FROM: T.-H. Peng

PURPOSE: To work with Dr. H. Oeschger and Dr. U. Siegenthaler at the University of Bern, Bern, Switzerland, on modeling the distribution of carbon isotopes in the ocean and on studying CO_2 uptake by using a general circulation model of the ocean carbon cycle, and to visit Dr. K. O. Munnich at the University of Heidelberg, Heidelberg, West Germany, to discuss CO_2 exchange and radon measurements.

SITES VISITED:

6/23 - 7/30/89	University of Bern	Bern, Switzerland	H. Oeschger U. Siegenthaler
7/31 - 8/4/89	Univ. of Heidelberg	Heidelberg, W. Germany	K. Munnich
8/5 - 8/31/89	University of Bern	Bern, Switzerland	H. Oeschger U. Siegenthaler

ABSTRACT: A joint project with Dr. Siegenthaler, comparing the distribution of radiocarbon in the ocean by using the one-dimensional ten-box PANDORA model and a three-dimensional general circulation model (GCM) of the ocean, was performed at the Climate and Environmental Physics Laboratory, Physics Institute, the University of Bern. Analysis of vertical and horizontal water fluxes in Princeton's GCM reveals that major mixing processes take place in the Antarctic Ocean, while the flow of North Atlantic deep water (NADW) is underestimated. By using average fluxes derived from the GCM, the distribution of radiocarbon is calculated in the PANDORA model. The preliminary results, showing that the ocean is much too young, can be attributed to the large circulation fluxes derived from the GCM. Many more computations and comparisons of results from Oak Ridge and Bern need to be done in order to understand the difference in the modeling results when simple box models and complicated GCMs of the ocean are used.

Radiocarbon data derived from lake sediments in Switzerland indicate that the record of atmospheric radiocarbon variations could be extended from 8,000 to 14,000 years before present. Discussions were held with Dr. Oeschger concerning how to interpret these data and how to link climate changes with ocean ventilation rates. Modeling the carbon cycle in the past and linking the atmospheric CO_2 variations with climate changes have great implications in understanding the mechanisms of the present carbon cycle and its relationship to future climate change. Redesign of the ten-box geochemical model of the global ocean includes new features of variable circulation patterns and fluxes in order to simulate glacial ocean circulation and to study the basic mechanisms that caused the atmospheric CO_2 concentration to rapidly change from 200 ppm during the glacial time to 280 ppm in the Holocene time. The most recent idea of a polar alkalinity hypothesis will be specifically built into the model to examine the causes of increased alkalinity in the Antarctic Ocean and to show how this increase could lower the atmospheric CO_2 concentration in the glacial time.

Radon measurements have been used in the open ocean for determining the rate of CO_2 exchange across the sea-air interface. In Heidelberg, radon in the natural system is measured by using a very sensitive proportional counter instead of a conventional photon detector. In addition to determining the sea-air CO_2 exchange rate, radon is also used at Heidelberg to assess the CO_2 flux from the unsaturated soil zone. If the relationship between soil types and radon fluxes can be established, the CO_2 fluxes from soil can be estimated by using the existing data base of soil type distribution. At the Institute of Environmental Physics at the University of Heidelberg, this idea is being applied to soil zones of the European continent. It would be an important contribution to the understanding of the carbon cycle involving soil carbon if a research project used the same radon method as that demonstrated at Heidelberg could be established in Oak Ridge for estimating the CO_2 fluxes from soil zones in North and South America.

1. Introduction

One of the major interests of the Global Carbon Cycle Research Program at Oak Ridge National Laboratory is to improve the understanding of the important role of the ocean in the global carbon cycle, especially in the uptake of excess CO_2, for the prediction of future atmospheric CO_2 concentration. Distribution of carbon isotopes in the ocean is used for calibrating the ocean carbon cycle models because it reflects the net results of the effects of ocean dynamics on carbon distribution in the ocean. At the University of Bern, many box-diffusion ocean models have been developed over the years by Drs. H. Oeschger and U. Siegenthaler. In addition, the recovery of the history of atmospheric concentration of

CO_2 from air bubbles trapped in ice deposits in polar regions has been initiated at this institution. Many new data concerning past atmospheric concentrations of CO_2, carbon isotopes, ^{10}Be, and other constituents have been generated continuously by this laboratory.

Working with Oeschger's group at the University of Bern on modeling the distribution of carbon isotopes in the ocean will certainly enhance our understanding of global carbon cycle dynamics and the effects of changes in climate on the distribution of carbon in various major active carbon reservoirs.

In recent years, it has been suggested that one of the main reasons that the box-diffusion types of ocean carbon cycle models do not take an expected portion of anthropogenic CO_2 is that the ocean is not properly represented by a few simple boxes in the box-diffusion models. To improve the simulation of the uptake of fossil fuel CO_2, the ocean carbon cycle model has to be more realistic with respect to both ocean dynamics and ocean geometry. As a result, three-dimensional ocean GCMs are used for transporting carbon in the ocean. To simulate CO_2 uptake, the carbon chemistry and marine biology have to be incorporated into such three-dimensional ocean GCMs. At Princeton University, the ocean GCM developed by K. Bryan of the Geophysical Fluid Dynamics Laboratory (GFDL) has been used for such studies. Dr. U. Siegenthaler of the University of Bern is working closely with Dr. Sarmiento of Princeton University in implementing the computational schemes for CO_2 uptake by using three-dimensional ocean models. They have made a few preliminary calculations of CO_2 uptake based on steady-state ocean conditions. Results of these calculations indicate that the amount of fossil fuel CO_2 taken up by a such a three-dimensional model of the ocean is not much different from that calculated by using a simple box-diffusion ocean model. It is an extremely interesting question to probe why a significant difference has not been found. Working with Dr. U. Siegenthaler may lead to an understanding of the heart of the problem.

In addition, Dr. Toggweiller of GFDL/National Oceanic and Atmospheric Administration (GFDL/NOAA) has successfully carried out simulations of the distribution of bomb-produced ^{14}C in the ocean by using a GCM-type three-dimensional world ocean model. To compare the mixing parameters used in the three-dimensional model and those used in the simpler box-diffusion ocean models such as the PANDORA model, the distribution of bomb-produced ^{14}C derived from three-dimensional model simulations can be used as if it were the field data. Adjustment of model parameters in the PANDORA model can then be made to simulate these ^{14}C field data. Comparison of these model calculations may shed some light on the difference between three-dimensional and one-dimensional ocean models when they are used for computing the CO_2 uptake. Working with Dr. U. Siegenthaler in this area is also a main part of my assignment to the University of Bern.

Paleocean circulation pattern and ocean ventilation rates play a very important role in determining the atmospheric CO_2 concentration during both the glacial and the interglacial periods. One of the biggest challenges to the ocean carbon cycle research is to interpret the rapid changes in atmospheric CO_2 concentration when climate changes from the glacial ice age to the current warm Holocene.

2. Research at Bern, Switzerland

The ^{14}C laboratory of the Physics Institute at the University of Bern has changed its name to Low-Level Counting and Nuclear Geophysics Laboratory. Because of the nature of the laboratory's research in recent years, Dr. Siegenthaler said that its name will be changed to Climate and Environmental Physics Laboratory. This laboratory is headed by Professor H. Oeschger; the teaching staff are Professors U. Siegenthaler, H. H. Loosli, and B. Stauffer. Other research staffs include Drs. B. E. Lehmann, A. Neftel, and J. Schwander. The eight graduate students working toward doctoral degrees are Fortunat Joos, Martin Lehmann, Marcus Leuenberger, Jose Rodrigues, Matthias Saurer, Andreas Sigg, Thomas Staffelbach, and Ralph Weppernig.

Dr. Oeschger oversees and leads the research in the Climate and Environmental Physics Laboratory of the Physics Institute. He is active in various international and intergovernmental scientific committees concerning greenhouse warming, future climate changes, and the global carbon cycle. Because of his active role, he is almost continually traveling to attend various important international meetings in the summer. I took advantage of one of his working weeks at Bern to discuss with him the modeling of natural ^{14}C distribution in the ocean in relation to changes of the ocean ventilation rate during the transition period from the last glacial to the present Holocene time. He pointed out that one of his students, Hugo Zbinden, had made measurements of ^{14}C variation in the atmospheric CO_2 in the period between 8,000 and 14,000 years before present. Although these measurements were made on the organic carbon deposited in the varved lake sediments in Switzerland, Dr. Oeschger and his student have good reason to believe that the ^{14}C variations are real. However, the interpretation of the variations is not fully formulated yet. These variations could have important implications with regard to the global carbon cycle and climate change. If a model can be developed to simulate such variations, we could learn the important mechanisms of oceanic processes during the last major climate changes from glacial to the Holocene time. Subsequent discussion with Dr. Siegenthaler in this same matter has resulted in my obtaining the data set listed in a paper to be published soon. A joint development of a model in the future to explore the causes of the ^{14}C variations could be very fruitful with regard to understanding the role of the ocean in the carbon cycle and its response to climate change.

Toggweiler of GFDL/NOAA at Princeton has successfully computed the distribution of natural ^{14}C in the ocean by using a coarse-grid (8° by 10°) nonseasonal GCM developed at GFDL. The simulated ^{14}C distribution in the Pacific and Indian Oceans was quite consistent with the observations made during the Geochemical Ocean Sections Study (GEOSECS) expeditions. In the Atlantic Ocean, especially the North Atlantic, however, the simulations show some distinct deviations from the observations. The simulated NADW contains less ^{14}C than the observations, implying that the flux of deep water formation in the GCM is underestimated. The advantage of such whole pictures becomes clear when results of a simple box model of the ocean are compared with those derived from the much more complicated three-dimensional ocean models. The three-dimensional distribution of ^{14}C in the ocean can be treated as a known data set for testing and calibrating the box model of the global ocean. By comparing the model parameters between box model and GCM, we expect to learn major differences in modeling the oceanic circulation processes. If relationships between the GCM and the box model could be established, one could make a more realistic ocean model with a simpler box model.

Siegenthaler works closely with the three-dimensional modeling group at Princeton headed by Sarmiento. He has obtained a complete GCM output of the radiocarbon simulation performed by Toggweiler, including circulation parameters and salinity, temperature, and ^{14}C distribution for every grid point in the GCM. To make a comparison between GCM and PANDORA, the GCM data had to be rearranged according to the structure of PANDORA. Bernhard Haller was hired to do this work. By working with Haller, the GCM data set was analyzed. With a limited amount of time available for such a task, the vertical and horizontal water fluxes were computed for each box in the PANDORA model. One of the most striking features is that the amount of total water flowing in and out of each PANDORA box is many times larger than the standard PANDORA circulation fluxes. For example, the box representing the deep water of the Antarctic Ocean has the largest total water flux of 50 sverdrups (Sv) in a standard circulation simulation. However, the GCM-derived total water flux for this same box is about 220 sv, about 4 times larger than the standard case. The other striking feature is that the GCM-derived circumpolar current dominates the circulation of the PANDORA model. For example, the strongest current is the water flowing from the northern Indo-Pacific thermocline polar outcrop region to the southern Atlantic thermocline polar outcrop region. This flow has a value of 104 Sv. The corresponding return flow from the Atlantic to the Indo-Pacific has a flux of 68 Sv. The total water flux in or out of the Indo-Pacific thermocline box is 325 Sv, while that for the Atlantic thermocline is about 177 Sv. Water exchange flux in the Antarctic surface box is 205 Sv, and that in the deep box is 230 Sv. These differences in PANDORA circulation fluxes between the standard case and the GCM-derived case imply that there are some fundamental differences in modeling the ocean with the box model and with the GCM. A further study to understand these differences is needed if compatible modeling results are to be achieved by using both box models and the GCM. Siegenthaler, Joos, and I agreed to investigate further these modeling methods and to study the current result of GCM-derived tracer fluxes including temperature, salinity, and ^{14}C, in addition to water fluxes.

Measurements of past atmospheric CO_2 concentrations were first obtained at Bern more than a decade ago by extracting the ancient air bubbles from polar ice deposits. One of the most important findings from these measurements is that the atmospheric CO_2 concentration increased from a value of 200 ppm at glacial time to 280 ppm at postglacial time before the industrial contamination. They also discovered the important fact that such changes took place very rapidly, on the order of within a few hundred years. Many hypotheses have been proposed to link the atmospheric CO_2 change with climate change. All of these hypotheses emphasize the important role of the ocean, especially the surface waters of the Antarctic Ocean. Siegenthaler has proposed one such polar nutrient hypothesis. The biological pump was believed to be much more efficient in the Antarctic Ocean during the glacial time so that more carbon was sent to the deep ocean and caused the drawdown of atmospheric CO_2 concentration. This would require a decrease in nutrient content at polar surface water and a huge consumption of O_2 in the deep water. However, the deep sea sediment records do not seem to support such conditions at the glacial time. Broecker and I recently proposed a polar alkalinity hypothesis which does not emphasize the decrease in nutrient content in polar surface water. Instead this hypothesis points to the increase of alkalinity in polar surface water and the increase of nutrients in polar deep water, which upwells to the surface water, to support the enhanced biological pump at the glacial time.

The main cause of such alkalinity and nutrient increases is the demise of the NADW, which is considered to be the main force in global ocean conveyer transport. Although this hypothesis predicts a rapid change of atmospheric CO_2 concentration of 80 ppm, it has not been subjected to model simulation. To perform a simulation of the demise of NADW and its consequent alkalinity increase at polar surface water and the atmospheric CO_2 decrease, a glacial ocean model is needed. Discussion with Siegenthaler has highlighted the need to break down the current PANDORA model into a series of independent circulation patterns so that the glacial circulation patterns can be simulated by turning these patterns on or off. Redesign of the circulation pattern of the PANDORA model became a major effort during this period at Bern.

I have identified 11 circulation patterns in the PANDORA ocean. Based on tracers and nutrient distribution in the current PANDORA model, the size of water flux for each circulation pattern can be derived. For simulation of the glacial ocean, variations in circulation fluxes can be modeled. The preliminary test run with the demise of NADW indicated that the atmospheric CO_2 concentration has decreased only from 282 ppm to about 263 ppm. If such conditions are maintained with additional rapid consumption of nutrients at polar surface water (this idea is suggested by Siegenthaler based on his polar nutrient hypotheses), the atmospheric pCO_2 decreases rapidly to about 243 ppm. These few test runs were made during the last few days at Bern. I did not have enough time to study whether the changes in alkalinity follow the predicted trend. Moreover, the biological production of $CaCO_3$ and SiO_2 in the model has to be changed according to the polar alkalinity hypothesis. I am looking forward to doing a number of interesting experiments with this new PANDORA model developed at Bern. If the connection between climate change and ocean response can be made through such experiments, we could learn the important role of the ocean in controlling the level of atmospheric CO_2 concentration.

3. Trip to Heidelberg, FRG

On July 31, 1989, I left Bern for the University of Heidelberg at Heidelberg, West Germany. I arrived in Heidelberg by car in the afternoon and visited Dr. K. O. Munnich, the director of the Institute of Environmental Physics. Discussion with Dr. Munnich revealed that there are about 100 people employed at the institute engaged in a wide variety of environmental research projects. Important research areas include carbon cycle (CO_2, CH_4); noble gases and freons in groundwater; application of stable isotopes such as D, ^{18}O, and ^{13}C; tritium and ^3He measurements; Lake Constance research; atmospheric chemistry including nitrogen oxides, O_3, and the OH radical; gas exchange in the ocean with waves (studied by using image processing); groundwater formation; soil research including estimates of gas fluxes by using radon as a major tracer; deep groundwater study for nuclear waste disposal; precision ocean ^{14}C measurements by using the conventional gas counting method and accelerator mass spectrometry (AMS); and deep sea sediment research, especially that regarding ^{10}Be and manganese distribution. Because it was vacation time for most staff, I could talk only with a limited research group. I indicated my desire to concentrate on subjects related to the carbon cycle and climate change research. I was happy to have a chance to interact with several members of the research staffs. A brief discussion of my interaction with them is given below.

Dr. Ingelborg Levin works on the carbon cycle by measuring variations of ^{14}C in the atmospheric CO_2 with time and locations in Europe. Although the atmospheric CO_2 is contaminated with bomb-produced ^{14}C, the seasonal input of fossil fuel CO_2 does dilute the ^{14}C activity with measurable amounts when it is determined with the use of Heidelberg's precision measuring instruments. The dilution is caused by the ^{14}C-free CO_2 gas from the burning of fossil fuels. Hence, monitoring the atmospheric ^{14}C variations can be used to determine the seasonal input of fossil fuel CO_2 with season and with locations. With her method, she shows that a more detailed spatial distribution of fossil fuel CO_2 release can be reconstructed than that given by Rotty's analysis.

Atmospheric ^{14}C variations over the ocean have also been monitored whenever a ship is available for collecting air samples. Significant latitudinal variations are detected. A lower ^{14}C level is found in the higher-latitude regions; in the Northern Hemisphere, it is interpreted as the dilution effect of the releases of the fossil fuel CO_2, which is most pronounced in the higher latitudes. However, in the Southern Hemisphere the fossil fuel CO_2 input is insignificant; therefore, the lower ^{14}C level must be caused by some other mechanism. Her current interpretation calls for an effective gas exchange between atmosphere and surface water of the southern high-latitude oceans, which are characterized by highly ^{14}C-deficient seawater. Also, the gas exchange rate is believed to be much higher in these regions than that in the lower latitudes. Hence, the atmospheric ^{14}C is lowered through the net transfer of ^{14}C from atmosphere to the southern surface ocean waters. I argued against such an interpretation because the low ^{14}C content of the Antarctic water is caused both by a brief contact of surface water with atmosphere before its descent and by the upwelling of subsurface waters that contain very little ^{14}C. It does not seem possible that a large amount of ^{14}C has been taken up by the Antarctic waters. It should be an interesting research problem to figure out why the atmospheric ^{14}C level in the southern high-latitude regions is much lower than that in the low-latitude regions.

Methane (CH_4) in the atmosphere has increased significantly in recent decades. Greenhouse effects caused by such an increase are considered significant when compared with those caused by the CO_2 increase. However, there are very few known CH_4 sources that should increase with industrialization or population increase. Measurements of the ^{14}C level of atmospheric CH_4 should shed some light on the sources of atmospheric CH_4 increase. However, such measurement is not easy to make because of the low concentration of atmospheric CH_4. Through cooperation with Eidgenössische Technische Hochschule at Zürich, the ^{14}C level of atmospheric CH_4 can be measured by AMS. Results of such measurements indicate that ^{14}C activity of CH_4 is compatible with that of atmospheric CO_2. Thus, atmospheric CH_4 is also contaminated with bomb-produced ^{14}C and, therefore, is involved in the active carbon cycle with modern carbon sources. However, measurements made with atmospheric samples taken from the Heidelberg area indicate that, instead of declining as most atmospheric contents of bomb-produced ^{14}C do, the ^{14}C level of CH_4 increased drastically in the last decades. The source of such local increase was traced and found to be linked with the high-pressure cooling nuclear power plant in Heidelberg. Because one of the characteristics of such power plants is the production of methane gas with a high level of ^{14}C during the cooling process, the interference of the ^{14}C produced by a nuclear power plant makes tracing the natural carbon cycle of CH_4 a rather difficult task.

Natural variations of ^{14}C in the atmosphere affect the precision radiocarbon dating method because the zero time ^{14}C level is not maintained at a constant value. Correction of radiocarbon ages requires accurate knowledge of natural ^{14}C variations. Tree ring ^{14}C measurements have been used for deriving such information.

Unfortunately, the current tree ring chronology goes back only about 8,000 years. Information regarding atmospheric ^{14}C variations during the transition from the last glacial period to the interglacial period is critical not only for ^{14}C dating but also for understanding the changes in ocean ventilation rates. Hence, to extend the natural ^{14}C measurements back in time is very important. Most current methods involve taking lake sediments with clear varves for counting the sediment ages. However, complications with respect to sedimentation rate changes have made such measurements less ideal than tree ring ^{14}C measurements. In Heidelberg efforts have been made to extend the tree ring ^{14}C record back to 12,000 years before present. Dr. Bernd Kromer is in charge of this project. Unfortunately, he was on vacation during the week of my visit to Heidelberg. Future contact with him is necessary to learn about such important ^{14}C variations through the last major climate change 11,000 years ago.

Carbon flux from the unsaturated soil zone is part of the active carbon cycle. Most current carbon cycle models have not seriously included the soil carbon flux because very little is known in this area. Major efforts have been made at Heidelberg to look into this carbon reservoir in the soil zone. One of the major problems with measuring the CO_2 flux from the soil zone is the respiration of organic material and vegetation roots, which may cause unrealistic carbon fluxes. To avoid local point sources and to estimate the gas transport in the unsaturated soil zone, radon gas is used as a standard tracer. Radon is evenly produced in the soil zone by the decay of radium. By measuring the soil radon profile and the radon gas flux out of the soil zone, the transfer function for soil gases can be derived and then used for estimating the true flux of other gases in the soil such as CO_2. The measurement of radon becomes a standard method for estimating CO_2 flux from the soil zone, provided the CO_2 concentration in the soil and the atmosphere can be measured precisely. Dr. Helmut Dörr is in charge of this project. A student working on this project is concentrating on determining the relationships between the radon flux and the soil types. If such linkage can be successfully found, the standard radon flux and gas transfer rates can be derived by analyzing the soil type distribution over various geographical locations. Dr. Dörr and his assistant have a plan for estimating radon and carbon flux from the European continent. It is hoped that by using this method a global soil CO_2 flux can be estimated in the future. I think we should also develop such a project in the United States so that a comparison can be made with Heidelberg and the radon and carbon fluxes can be estimated for the North and South American continents. Future contact with Heidelberg is necessary to make such a project possible.

The distribution of noble gases in groundwater has been used as a tracer for studying groundwater movement and paleotemperature changes. Discussion with Dr. M. Stute has revealed that if the saturation of noble gases in groundwater is assumed, measurements of the concentration of noble gases can give groundwater temperature when gas solubility is known. If groundwater can be dated, past temperature variations with time can be reconstructed. This may offer an opportunity to reconstruct the temperature records for the climate changes in the past 20,000 years. Precision groundwater measurements and hydrological modeling play an important role in such studies. Heidelberg University has the best instrumentation for such measurements. However, box models are used for its groundwater modeling. Dating of the groundwater seems to be based on comparison of the distribution of noble gases measured with that computed with the model. Nevertheless, we can learn how groundwater moved from recharged areas. Its application to paleoclimate study seems quite promising.

APPENDIX

TRIP ITINERARY

June 22-23, 1989	Travel from Oak Ridge to Bern, Switzerland
June 24-25	Weekend
June 26-July 30	Work with Drs. H. Oeschger and U. Siegenthaler on modeling distribution of carbon isotopes in the ocean and CO_2 uptake using GCM-type model, respectively
July 31-August 4	Heidelberg, West Germany - To discuss CO_2 exchange work with Dr. K. O. Munnich
August 5-August 31	Bern, Switzerland - To continue work with Drs. H. Oeschger and U. Siegenthaler
September 1	Return to Oak Ridge, Tennessee

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