Geochemical Constraints on Ocean General Circulation Models

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Introduction.

A better understanding of the manner in which the ocean operates is essential to our preparation for the consequences of the generation of CO_2 by fossil fuel burning. Examples are as follows:

1) The ocean will ultimately take up a major fraction of the CO_2 we produce, but this uptake is retarded by the slow mixing rates. In order to predict the uptake, we must develop and validate general circulation models for the ocean.
2) During glacial time large global climate changes occurred. The changes were abrupt happening in a few decades. The trigger for these changes appears to have been reorganizations of the large-scale thermohaline circulation of the ocean. Models suggest that if the CO_2 content of the atmosphere rises to more than 700 ppm, then a possibility exists that another such reorganization might occur. Hence, we must learn more about the factors influencing deep-water formation both in the northern Atlantic and in the Southern Ocean.

The thrust of the research carried out under this grant was to develop constraints based on the distributions of chemicals and tracers in the sea. Our accomplishments are outlived in the following paragraphs.

The Distribution of Natural and Bomb-Testing Radiocarbon in the Sea.

The distribution of radiocarbon in the sea constitutes the most powerful constraint on ocean general circulation models. This radiocarbon has two sources: neutrons from cosmic rays and neutrons from nuclear explosions. The distribution of the first type (i.e., natural ^{14}C) should be close to steady state. The distribution of the second type (i.e., bomb ^{14}C) constitutes a transient. While in models the two types of ^{14}C can be easily kept separate, in the real ocean the two types of ^{14}C are indistinguishable. Thus, a major aspect of our research has been to find a means to separate the bomb and natural components. We have developed a strategy to do this that involves three pieces of information:

1) A limited number of ^{14}C measurements on pre-nuclear surface water and on archived coral and shell samples.
2) The penetration depth of bomb produced tritium.
3) The linear relationship between natural radiocarbon and dissolved silica in the thermocline of the world ocean.

We have used this strategy to map the distribution of natural radiocarbon and also that of bomb radiocarbon at the time of the GEOSECS, TTO, and SAVE surveys. Bob Key at Princeton is extending this strategy to the comprehensive WOCE survey. The details have been published in a paper by Broecker et al. 1995.

In addition, we conducted an interim mini survey of the northern Atlantic designed to fill in the evolution of the bomb ^{14}C transient between the TTO survey (1980) and the WOCE survey (1999). The results of this survey have been published by Severinghaus et al. 1996.

Production of Deep Waters in Today's Ocean.

We have used the distributions of natural radiocarbon and of a quasi-conservative tracer, we call PO_4^*, to define the source locales and production rates of deep waters in today's ocean.

PO_4^* is defined as follows:

$$PO_4^* = PO_4 + O_2/175 - 1.95\ \mu mol/pg$$

Where 175 is the Redfield coefficient relating oxygen consumption to phosphate release during respiration. This parameter is very useful because of the large contrast between its value for deep waters formed in the northern Atlantic (0.73 $\pm$ 0.03) and those formed around the perimeter of the Antarctic continent (1.95 $\pm$ 0.05). Waters from these two sources are thoroughly blended in the circum Antarctic deep raceway. From there they flood northward into the deep Pacific and Indian Oceans. This mix has a PO_4^* value of 1.37$\pm$ 0.05 requiring that about 45 percent of the global deep water is produced in the northern Atlantic and about 55 percent in the Southern Ocean.

Assuming that the distribution of natural radiocarbon in the deep ocean is at steady state, we have been able to constrain the rates of deep-water formation to be about 16 and 13 Sverdrups (i.e., one million cubic meters per second) respectively.

Measurements of the inventory of freons in the deep Southern Ocean indicate that the natural ^{14}C based flux (an average for 10^3 yrs) is consistent with the recent ventilation rate (an average for 10^1 yrs).

This result points up a basic flaw in our understanding of deep-water formation in the Southern Ocean. Physical oceanographers have long postulated that the primary locale for deep water formation in the Southern Ocean is in the Weddell Sea down stream (i.e., eastward) of the Antarctic Peninsula. Yet the estimates of "ventilated" deep-water production in this embayment all lie in the range 1 to 5 Sverdrups. So a task for the future is to sort out where the remaining 10 or so Sverdrups form.

The details of these calculations are in press in the *Journal of Geophysical Research* (Broecker et al. 1998).

The Helium-3 Constraint.

Primordial ^{3}He is being released into the deep ocean along ridge crests in association with sea floor spreading. As part of the GEOSECS program, the excess ^{3}He (i.e., over the atmospheric component) was mapped globally. In cooperation with Ernst Maier-Reimer of the Hamburg MPI Group, we recreated this input in a global circulation model. The resulting steady state distribution in the model to a large extent matched the observed. A major exception was the deep Atlantic where the model predicted a measurable excess (not accounted for by the inflow of ^{3}He rich Southern Ocean waters) where none is seen in the measurements. This suggests that an amount of excess ^{4}He is being added to the deep Atlantic offsetting the input of ^{3}He.

The value of this tracer experiment is that the model results predict where the deep water upwells to the surface (and hence loses its excess ^{3}He to the atmosphere). Were fossil fuel CO_2 in the future to be liquefied and disposed of in pools on the sea floor, then it will become important to know how long it will remain there and where it will eventually reach the surface. Unfortunately, we as yet have no tracer that allows us to quantify upwelling. However, model-model comparisons using ^{3}He will at least tell us to what extent models are self-consistent.

A paper detailing these modeling results authored by Farley et al. (1995 has been published.

Thermohaline Circulation Reorganizations.

Results of radiocarbon reconstructions for atmospheric CO_2 provide a convincing case that indeed the onset of the Younger Dryas cold period was triggered by a shutdown in deep water production in the northern Atlantic. This reconstruction also makes clear that the shutdown of the transport of newly-produced radiocarbon into the deep sea continued for only the first 200 years of the 1200-year duration Younger Dryas. As conditions in the northern Atlantic basin remained uniformly cold during the entire 1200 years, the resumptionof radiocarbon transport into the deep sea could not have been via the Atlantic's conveyor circulation. Rather, as suggested by Broecker 1998, the ventilation likely occurred in the Southern Ocean. This would explain the antiphasing of the temperature fluctuation between the Antarctic and most of the rest of the world during the interval of deglaciation (and also for the Dansgaard-Oeschger events of marine isotope stage 3). Broecker refers to this as the bipolar seesaw.

The inclination of the ocean's thermohaline ventilation to seesaw between the two major source regions has implications to the near future. As the planet warms, the density of waters in the high latitude source regions will tend to fall. The warming of the surface water, the melt back of sea ice, and the increase in precipitation will drive this decrease. As the rate of decrease is very likely to differ between north and south, we run the risk of upsetting the current balance and cause deep ventilation to reorganize or even to stop for a century or so. As outlined by Broecker 1997, this could have awesome consequences to food production.

Iron Fertilzation.

The late John Martins' hypothesis, that in those regions of the surface ocean receiving little fallout of dust, iron is the limiting ingredient, has now been proven correct. This brings up two possibilities. First, iron could be used to mitigate the rise in CO_2 content of the atmosphere. In published papers, Broecker and Peng 1992 and Peng et al 1992, show that even if the available NO_3 and PO_4 in surface waters of Southern Ocean could be completely utilized in this way, the reduction in CO_2 content in the atmosphere would be even after 100 years only about 70 ppm. Were this continuous fertilization to be stopped, the 70 ppm would return on more or less the same time schedule as it was removed. Finally, the consequences of such action to the ecology of the Southern Ocean would be profound.

More interesting perhaps are the implications to the low CO_2 content of the glacial atmosphere. In a paper now accepted for publication in *Paleoceanography,* Broecker and Henderson (in press), we propose that the large excess of dust falling on the glacial ocean led to a proliferation of nitrogen fixing bacteria in the warm temperate ocean. The increased in the oceanic nitrate inventory created in this way fueled plant productivity thorughout the surface ocean and hence cause the 80 ppm drawdown of atmospheric CO_2.

Radium-Barium Dating.

Gideon Henderson and Synte Peacock had hoped to use the ratio of ^{226}Ra to barium in shells found on raised beaches in the Antarctic to reconstruct the $^{14}C/C$ ratio in surface waters close to the continental margin. Gideon spent several weeks at the Open University in London, England learning the procedures used to do ^{226}Ra by isotope dilution mass spectrometry. But as his initial results were not encouraging, he abandoned this effort and went on to other aspects of his post doctoral research. Synte turned her attention to modeling θ, S, $^{14}C/C$, PO_4^* in the deep sea.

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