Carbon cycle

Carbon dioxide circulation through ocean and atmosphere

from Wallace S. Broecker

JUST over three years ago measurements of the CO_2 content of air from polar ice cores were independently published by groups in Bern[1] and Grenoble[2]. Both groups concluded that the CO_2 content of the atmosphere during the last glacial period was about two-thirds of that in post-glacial times. Oceanic and atmospheric contributions to the carbon cycle must have been responsible for changes on such a time scale and two papers on pages 621 and 624 of this issue of *Nature* describe the first results of computer models designed to clarify the roles of the ocean–atmosphere system[3,4].

The dramatic changes in atmospheric CO_2 content revealed by the ice cores immediately captured the interest of the geochemical and climatological communities for it was the first clear evidence for significant natural changes in the atmosphere's trace gas content (and hence in its greenhouse capacity). I jumped on the result and tried to explain it[5].

It was easy to show that it must have originated in the ocean and was not the result of the warming of the ocean surface which accompanied deglaciation. I came up with two viable hypotheses, consistent with the rather strong constraints imposed by the ^{13}C record for the surface and deep waters of the sea as recorded in the shells of planktonic and benthic foraminifera in deep-sea sediments.

Both hypotheses involved changes in the relative abundances of carbon to the limiting nutrients, phosphorus and nitrogen. In the first hypothesis, this change was caused by the removal of organic matter to the sediments deposited along the margins of the sea as they were flooded by the water released from the melting glaciers. In the second, the change was induced by a decrease at the onset of post-glacial time in the ratio of carbon to nitrogen and phosphorus in the organic matter falling from the sea surface (see ref. 6 for the detailed arguments).

Early last year the Bern group dropped another 'bomb' on the climate community. Working with samples from a new ice core from the Dye 3 site in Greenland the group showed that the changes in atmospheric CO_2 associated with the close of glacial time occurred in a period of less than 1,000 years; moreover, for several time spans of about 1,000 years within the glacial period, coinciding with warming recorded by ^{18}O to ^{16}O shifts[7], the CO_2 content returned more than half way to its post-glacial value[8]. Since the bulk chemistry of the ocean–atmosphere system cannot change within 1,000-year periods, my sedimentation hypothesis dropped from contention to be replaced by an alternative hypothesis generated with Taro Takahashi.

We suggest that because carbon dioxide can be transported through the atmosphere from one region of the ocean surface to another while nitrate and phosphate cannot, it is conceivable that changes in atmospheric CO_2 content are induced by changes in the deep-sea ventilation rate[9], in which case the rise in CO_2 content of the air at the close of glacial time might simply have been the result of a decrease in that rate.

Groups from Princeton, Bern and Harvard have also investigated lower-than-present concentrations of nitrate and phosphate in polar surface water during glacial time. Papers from the first two groups appear on pages 621 and 624 of this issue; the third group has a paper in press in *Journal of Geophysical Research.*

While differing in detail, all three papers call on a more efficient utilization by plants of the nitrate and phosphate reaching the sea surface in polar regions than elsewhere. The resulting drop in the nutrient content of Antarctic surface waters leads to a reduction in the total oxidized carbon (ΣCO_2) content of these waters and also in the CO_2 content of the atmosphere. Knox and McElroy suggest that the more efficient utilization of nutrients is related to changes in the amount of light reaching the polar regions[10]; Siegenthaler and Wenk opt to explain it by an increase in the residence time of water at the Antarctic surface[4]; and Sarmiento and Toggweiler conclude that it must be the result of changes in either illumination or residence time[3].

Discussion among the interested parties at a recent meeting* (reported in ref. 11) led to agreement on several points. First, the ideas we now have are preliminary probes into a new and very fascinating realm of science, namely how the flow of carbon, nitrogen and phosphorus through the ocean-atmosphere system responds to perturbations in the conditions of our planet's surface.

Second, the record of the $^{13}C/^{12}C$ ratio of the ocean and atmosphere held in the ice cores will be the key to deciding the relative importance of changes in organic residue composition, ventilation rates and polar nutrient composition in the low CO_2 concentrations of glacial times. As the carbon incorporated by plants is depleted in ^{13}C relative to ^{12}C, changes in the efficiency of utilization of surface-water nutrients will lead to changes in the $^{13}C/^{12}C$ ratio in the ΣCO_2 of surface water (and hence in planktonic foraminifera). At the meeting, H. Oeschger of the Bern group indicated that the vital carbon isotope record for the atmosphere based on measurements on CO_2 extracted from ice cores would soon be available. Meanwhile, N. Shackleton (University of Cambridge) revealed that his unpublished $^{13}C/^{12}C$ records for planktonic forams from sediment cores taken in the Atlantic sector of the Antarctic (50–52°S) show that the $^{13}C/^{12}C$ ratio during peak glacial time is 0.3–0.5‰ more negative than during peak interglacial time. Such a change is at odds with the Antarctic nutrient models. If, therefore, these records prove to typify Antarctic surface waters there will be another casualty among the hypotheses.

Third, the much lower dissolved oxygen content of glacial deep-sea water demanded by the three nutrient-based models (that is, sediment storage, residue composition and polar surface water composition) does not seem to be in evidence in the sedimentary record.

Fourth, if, as seems likely from results presented by Michel Andree of the Bern group, the application of the accelerator ^{14}C dating method (see these columns, R. E. M. Hedges and J. A. J. Gowlett *Nature* **308**, 403; 1984) to hand-picked planktonic and benthic foraminifera will enable direct estimates to be made of the rate of ventilation of the deep sea during glacial time, the results should provide a valuable focus for the next generation of hypotheses.

Just as the results of CO_2 measurement on ice cores have captured the interest of those concerned with climates of the past, they will surely turn the heads of those concerned with climates to come. Will anthropogenic changes in atmospheric CO_2 ultimately force a change in the mode of operation of the ocean? The four teams who are searching for an explanation of the ice-core CO_2 results agree that there must have been major changes in the past in ocean operation, with some unknown sequence of events causing the balance to tip from one mode of operation to another. Will the warming of the planet that will surely occur during the next hundred or so years tip the balance again? □

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* The Chapman Conference on 'Natural Variations in Carbon Dioxide and the Carbon Cycle', held in Tarpon Springs, Florida, 9-13 January 1984.

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