The Carbon Cycle and Climate Warming

Learning how carbon cycles through the environment, with and without human intervention, is crucial to predicting the greenhouse effect

The burning of fossil fuels and the resulting carbon dioxide greenhouse effect will heat Earth's atmosphere to new high temperatures. Researchers agree on that much (*Science*, 4 November, p. 491), but the current question is exactly how far and how fast the temperature will rise. A key element in predicting that rise is predicting the comings and goings of carbon and carbon dioxide in the tightly linked system of ocean, rock, air, and plant. Ecologists, oceanographers, and geochemists gathered in Knoxville* at the end of October to consider just how well they understand the carbon cycle. Better than they did in the past, seemed to be the answer, but far from well enough to say how much of the carbon dioxide released in coming centuries will remain in the atmosphere to warm the climate.

From the beginning of the meeting, it was made clear that understanding the carbon cycle is not the only problem in predicting future warming. A major uncertainty is the timing and magnitude of future releases of carbon dioxide from the burning of fossil fuels. Today, 1.1 tons of carbon as carbon dioxide is released every year for every person on Earth. Americans contribute an impressive 5 tons per person per year.

Fossil fuels such as coal are available in what, for all practical purposes, are unlimited quantities, but economists cannot say just how much will be burned or how fast reserves will be consumed. The best guess of the recent National Research Council report (*Science*, 4 November, p. 491) is that yearly releases will quadruple by 2100, but there is a 50 percent probability that annual releases will fall somewhere between 12 billion and 55 billion tons. Thus, atmospheric carbon dioxide concentrations will inevitably increase, most likely doubling sometime late in the next century.

With this unavoidable social uncertainty in mind, carbon cycle researchers turned to how they might narrow the uncertainty in their own field, the first question being the concentration of atmospheric carbon dioxide before fossil fuel burning began to inflate it. They have no reliable, direct record of atmospheric carbon dioxide before 1958, but they would still like to know how much carbon dioxide has been added to the atmosphere and thus how far along the road the world has come toward a detectable warming.

If fossil fuel is assumed to be the only source of carbon dioxide and about half remains in the atmosphere, the preindustrial concentration should have been about 290 parts per million by volume. If that were the case, climatologists might have several decades to wait before the greenhouse warming became evident above the background of climatic noise. Or, computer models of greenhouse climate effects could be too sensitive to rising carbon dioxide. Recent estimates suggest that climate models are not that far off and climatologists may not have to wait that long.

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Those estimates are based on indirect measurements that indicate lower concentrations of atmospheric carbon dioxide in the past than fossil fuel burning alone would suggest. Hans Oeschger and Bernard Stauffer of the University of Bern reported that Greenland and Antarctic ice up to 1000 years old contains air having about 270 parts per million carbon dioxide. The air was trapped as accumulating snow slowly turned to ice, sealing the air into bubbles. The fidelity of this ice record has not been established beyond a doubt, but Oeschger believes that 270 parts per million is probably within 10 parts per million of the true value.

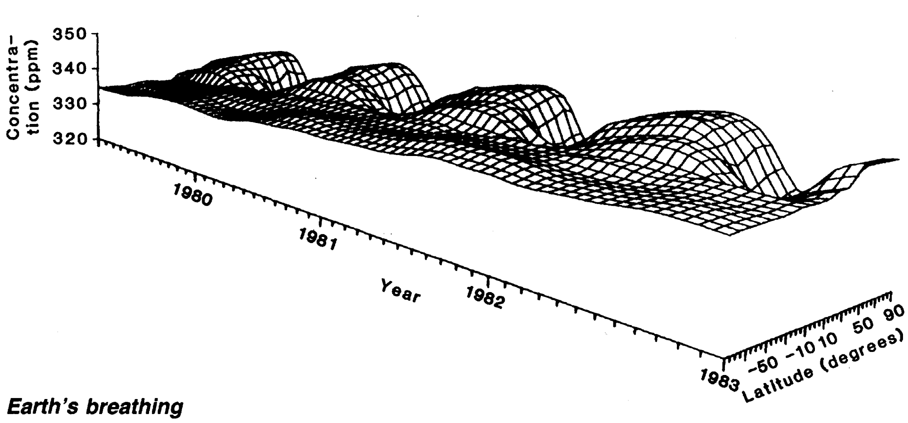
Less direct measurements of past carbon dioxide concentrations can be made through isotopic analysis of tree rings. The low ratios of carbon-13 to carbon-12 in fossil fuels reflect the low ratio in the plant material that formed the fuels. Released to the atmosphere and incorporated into living plants, this fossil fuel carbon further lowers the isotopic ratio of modern plants. Hans Freyer of the Nuclear Research Center at Jülich, West Germany, reported that a compilation of his tree ring analyses and those of others places preindustrial atmospheric carbon dioxide concentrations at about 260 parts per million. From six trees on the U.S. Pacific coast, Minze Stuiver of the University of Washington estimated a preindustrial value of 276 parts per million.

Apparently, the present 340 parts per million of carbon dioxide represents an initial value of roughly 270 parts per million plus the contribution of fossil fuel burning and some additional source. The most discussed possibility for the additional source has been the biosphere, principally through the clearing of forests and the destruction of soil organic matter through cultivation (*Science*, 20 June 1980, p. 1358). Everyone now agrees that the biosphere has been a source over the past century, but oceanographers still cannot find a way to accommodate the carbon dioxide from a recent, large additional source in the ocean, where it presumably went after release to the atmosphere.

Richard Houghton of the Marine Biological Laboratory in Woods Hole presented the current results from his ambitious attempt to estimate world biosphere releases during the past century from changes in land use. According to his calculations, the biosphere released 180 billion tons of carbon since 1860, mostly since 1920. It is still releasing 2.6 billion tons per year, according to the model, although Houghton concedes that there is an uncertainty of 1 billion tons in this annual rate.

Charles Hall of Cornell University suggested that Houghton's uncertainty, at least in the clearing of tropical forests, might be larger still. Hall calculates carbon releases from tropical deforestation alone that are less than 1 billion tons per year, which barely overlaps Houghton's range at its lower end. Outside the tropics, noted Orie Loucks of Butler University, the differences between models are even greater, some calling for releases

*The Global Carbon Cycle: Analysis of the Natural Cycle and Implications of Anthropogenic Alterations for the Next Century, held 31 October to 2 November in Knoxville, Tennessee. The general chairmen were D. E. Reichle, J. R. Trabalka, and C. R. Richmond of Oak Ridge National Laboratory.



Earth's breathing

Not only is atmospheric carbon dioxide increasing due to human activities, but Earth also "breathes." This 4-year record is based on results from about 20 sampling sites around the world operated by the National Oceanic and Atmospheric Administration. The gradual annual increase of about 0.4 percent is most evident at high southern latitudes (the near edge). In the Northern Hemisphere, where most of the land surface and thus most nontropical land plants reside, the uptake of carbon dioxide during the growing season draws down the concentration in summer. Decay processes drive it back up during the winter. The more muted expression of this part of the carbon cycle in the Southern Hemisphere is 180 degrees out of phase with that in the north. [*Source: Richard Gammon*]

from the temperate zone and others for net uptake there. A major uncertainty seems to be what the Soviet Union is doing to its forests.

Looking at other parts of the cycle, where biospheric releases might be in transit or eventually deposited, researchers can find no evidence of a large, non–fossil fuel source. Tsung-Hung Peng of Oak Ridge National Laboratory and Wallace Broecker of Lamont-Doherty Geological Observatory looked for evidence of additional carbon being deposited as organic matter in the ocean. They compared oxygen and nutrient concentrations determined during surveys of the North Atlantic in 1972 and 1981 and found no changes that they could attribute to an increase in the rate of storage of carbon as organic matter in the sea or on the sea floor, at least in the moderately productive North Atlantic.

Charles Keeling of Scripps Institution of Oceanography noted that his analyses of atmospheric carbon dioxide across the equatorial Pacific since 1978 do not require a large biospheric source either. There is a carbon dioxide peak at the equator, Keeling said, which can be explained by the expected release of carbon dioxide from deep seawater rising to the sea surface there. Keeling found no sharp change across the equator in the carbon isotopic ratio of atmospheric carbon dioxide, which is also consistent with an oceanic source at the equator but not a large terrestrial biospheric source.

Thus, Keeling and a number of other researchers would prefer a modest biospheric source at present, perhaps 1 billion tons of carbon per year or less, which would be small compared to the present 5 billion tons per year from fossil fuels. The largest pulse of biospheric release might then be pushed back to the late 19th century, due perhaps to a wave of "pioneer agriculture." Increasing fossil fuel releases would eventually swamp any future biospheric releases. That would make the biospheric source problem largely one of deciphering the past, not predicting the future.

The ultimate aim of carbon cycle research is to predict how the concentration of carbon dioxide in the atmosphere will vary as humankind pumps more and more of it into the atmosphere. The usual approach is to divide the world's ocean, air, and land into separate boxes, fluxes in and out of each box representing the workings of one part of the carbon cycle. Early models consisted of three boxes—the atmosphere, the surface ocean where atmospheric carbon dioxide would dissolve, and the deep sea where it would eventually dissolve carbonate sediments. In an attempt to match these box models to what is known about the present-day workings of the carbon cycle, modelers have increased the number of boxes, first from 3 to 12 and now reportedly to 84. One model of the North Atlantic under development by Jorge Sarmiento of Princeton University has 100,000 "boxes" like those in a weather forecaster's computer model of the atmosphere. None of these models yet duplicates the present well enough to attempt predicting the future.

Several speakers cautioned that the future might have surprises in store that have not yet been included in even the most sophisticated models. William Jenkins of Woods Hole Oceanographic Institution recalled the recent discovery of changes in the temperature and salinity of the deep North Atlantic during less than a decade (*Science*, 12 November 1982, p. 670). If the deep sea can change with such surprising swiftness, presumably in response to atmospheric changes, Jenkins asked, how will the deep ocean and its capacity to remove carbon dioxide from the atmosphere respond to the inevitable greenhouse warming?

Oeschger and Stauffer argued that glacial ice does indeed contain evidence of rapid changes in atmospheric carbon dioxide in tandem with climatic changes. Ice analyses by several laboratories have already shown that atmospheric carbon dioxide rose from about 190 to almost 300 parts per million as the climate warmed at the end of the last glacial period. That shift, whether cause or effect, required thousands of years. Oeschger and Stauffer's detailed sampling of ice formed in the middle of the last glacial period 40,000 years ago has now revealed comparable changes requiring little more than a few hundred years. A data plot showed a stunning lockstep of changes in carbon dioxide as large as 75 parts per million and changes in isotopic composition reflecting temperature changes. Oeschger argued that the cycling of both properties could not be due to melting and refreezing of the ice, because it formed when the climate was much colder than it is today. Earth did seem to be jumping between different stable modes of operation of the climate system, he said.

Eric Sundquist of the U.S. Geological Survey in Reston, Virginia, also warned that the carbon cycle may not operate in the future the way it has in the recent past. To make his point, he created a relatively simple model including the atmosphere, ocean, and ocean sediments. Today, anthropogenic carbon dioxide that reaches deep-sea sediments dissolves the carbonate in them and is removed from the cycle. Thus, sediments are a sink for carbon dioxide. But when the carbon in all the available fossil fuels is injected into the atmosphere in a pulse centered in the year 2100 (a worst-case scenario), the neutralization of carbon dioxide by the sediments slows to a halt. Carbonate at the sediment surface dissolves faster than bottom-dwelling animals can churn it up from beneath, a protective layer of noncarbonate sediment forms, and neutralization becomes limited by the slow rain of carbonate from the ocean surface. In this model at least, carbon dioxide levels are still doubled after 12,000 years, in startling contrast to the perspective of years or a century taken in most discussions of the carbon cycle.—**Richard A. Kerr**