GLOBAL CHANGE

Fugitive Carbon Dioxide: It's Not Hiding in the Ocean

Missing: 3 billion to 4 billion tons of carbon every year. May be hiding in the ocean or on land, in plants. If found, contact geochemists and terrestrial ecologists trying to understand how carbon cycles through the atmosphere, ocean, and biosphere. Reward: a better prediction of future greenhouse warming.

The fugitive carbon is the difference between the 7 billion or so tons that spew as carbon dioxide from smokestacks and burning tropical forests and the 3.4 billion tons known to stay in the atmosphere. Finding the other 3 billion or 4 billion tons has frustrated researchers for the past 15 years. The oceans certainly take up some of it—but not all, researchers are increasingly convinced. And they will draw support from a paper in this issue of *Science* (p. 74), in which a group of oceanographers reports that the first attempt to track down the missing carbon in the oceans using its isotopic markings has turned up only about 2 billion tons. That leaves a billion tons or more still at large and fuels suspicions that plants have been taking up the rest. If so, plants may be helping to fend off global warming for now. But for how long?

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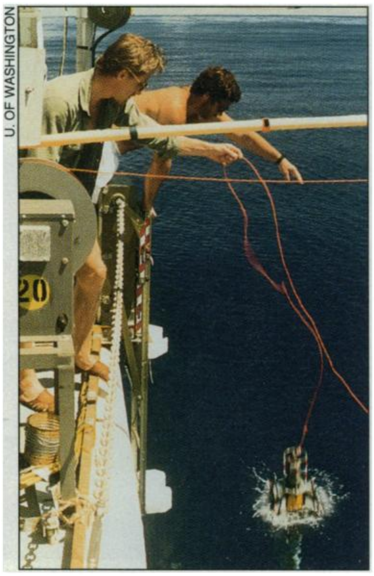

Fishing for carbon. Oceanographers can't find the missing carbon.

Any forecast of global warming has to be based on how much of the carbon dioxide released by human activity will remain in the atmosphere, and predictions vary by 30% depending on the mix of oceanic and terrestrial processes assumed to be removing the gas. What's more, those predictions assume that the processes at work today will go on operating. But not knowing where all the carbon is going raises the unnerving possibility that whatever processes are removing it may soon fall down on the job without warning, accelerating any warming.

Such concerns add urgency to the question of whether the ocean harbors the missing carbon. But there's no simple way to find out. The obvious strategy might seem to be to measure the carbon content of the ocean repeatedly to see how much it increases year by year. The trouble is that several billion tons of added carbon, though impressive on a human scale, are undetectable against the huge swings in ocean carbon that occur from season to season, year to year, and place to place.

Fortunately, the carbon emitted by human activity carries a distinctive tag, by which its movements can be followed. The tag—a kind of isotopic fingerprint—consists of the ratio of carbon-13 to carbon-12. Both fossil fuels and plants contain a smaller proportion of carbon-13 than atmospheric carbon dioxide. As a result, the carbon dioxide emitted when the fuels or plants are burned is depleted in carbon-13—a signal that migrates through the atmosphere and penetrates the ocean as it exchanges carbon dioxide with the atmosphere. The rate at which the signal increases from year to year should give a measure of how fast the ocean is taking up manmade carbon.

As they report in this issue of *Science*, Paul Quay of the University of Washington and his colleagues traced this signal from one end of the Pacific to the other, using measurements made in 1970 and 1990 along ship tracks extending from near Antarctica to the Gulf of Alaska. From the increase in the signal's strength and depth of penetration—up to 1000 meters—Quay and his colleagues were able to estimate how much manmade carbon had entered the Pacific over the period.

But these researchers wanted a number for the entire ocean, not just the Pacific. Lacking carbon-13 measurements beyond the Pacific, they fell back on measurements of radioactive carbon-14 produced in the atmosphere by the nuclear bomb tests of the early 1960s. Carbon-14 isn't a tracer for fossil-fuel or biomass carbon, but it too enters the ocean as carbon dioxide, providing a gauge of how rapidly atmospheric carbon dioxide from all kinds of sources is permeating the ocean. From the observed carbon-14 penetration of the Atlantic and Indian oceans, Quay calculated a global ocean uptake of 2.1 billion tons of manmade carbon per year. That leaves the carbon auditors with at least a billion-ton shortfall.

But geochemist Pieter Tans of the National Oceanic and Atmospheric Administration in Boulder thinks the carbon deficit may be bigger still. Two years ago Tans and his colleagues used the variation of atmospheric carbon dioxide between hemispheres and between the atmosphere and the ocean surface to estimate that the ocean could be taking up at most only 1 billion tons of carbon. He isn't ready to concede the higher figure. "The analogy with carbon-14 is clever, [and] it does work to first order," he admits. "But it could be off by a significant amount." Quay and company do calculate an uncertainty of plus or minus 35% (one standard deviation), much of it attributable to the limited geographic coverage. But in the carbon cycle game, that's considered adequate if not exact.

Models agree. Computer models of carbon dioxide exchange between the ocean and atmosphere tend to support the Quay group's figure. Ocean modeler Jorge Sarmiento of Princeton University and his colleagues have recently simulated the ocean uptake of carbon using the most sophisticated computer model yet applied to the problem. The simulated uptake was 1.9 billion tons per year, in line with the carbon-13 estimate.

In a separate study, Sarmiento and geochemist Eric Sundquist of the U.S. Geological Survey in Woods Hole have reevaluated the Tans work and pointed out three corrections they say would bring it more or less into line with the results based on carbon-13 and the latest ocean models. Tans concedes that the corrections "go in the right direction, but I don't think it's enough" to close the gap.

Although the geochemists and oceanographers continue to dicker about the exact numbers, these recent results only strengthen their conviction that the ocean is in no position to take up all the missing carbon dioxide. That leaves the terrestrial biosphere, where plants absorb carbon dioxide and lock it away in their tissues. Terrestrial ecologists have little evidence that the biosphere is currently taking in more carbon dioxide than it releases. Some speculate, though, that temperate forests, still growing back after being leveled in the 18th and 19th centuries, may have tipped the balance toward carbon dioxide uptake (see report by Kauppi and colleagues on p. 70). Others suggest that vegetation in the tropics, "fertilized" by the rise in atmospheric carbon dioxide, might be stowing away some of the missing carbon.

Whatever is going on, researchers are eager to sort it out before one or more of these mysterious sinks stops working. The fertilizing effect of carbon dioxide, for example, might run up against some physiologic limit. Then the excess carbon would come out of hiding, suddenly turning up in the atmosphere. That is not how researchers want to find their fugitive.

–Richard A. Kerr