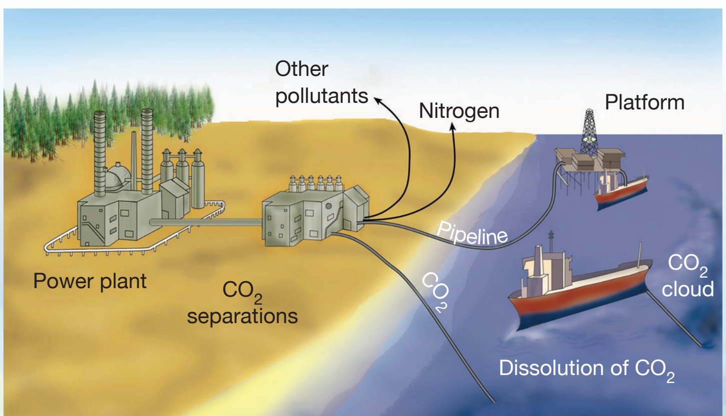
The Siren Call of the Seas

Sequestering Carbon Dioxide

MOST experts now agree: increased emissions of greenhouse gases, especially carbon dioxide, are responsible for the overall warming of our planet. Yet, reversing the rate of these emissions, or even holding it steady, appears to be a nearly impossible task. In the 20th century alone, the human population quadrupled, and primary power consumption increased 16-fold. During that same time, atmospheric carbon dioxide increased from about 275 to 370 parts per million—and demand for power continues to grow.

Scientists cannot fully predict the future effects of carbon dioxide buildup. However, most of them agree that serious environmental consequences are possible unless the management of carbon dioxide emissions improves.

The burning of fossil fuels—coal, oil, and gas—is expected to be the main source of energy for the foreseeable future. For instance, according to the International Atomic Energy Agency, fossil fuels will account for almost all new electric power generating capacity during the next 20 years: 78 percent for the developing world, up to 97 percent for transition economies, and 89 percent for the developed world. Doing away with all of the carbon dioxide that results from power production is unrealistic. Instead, scientists are focused on finding methods to stabilize the amount of carbon dioxide being added to the atmosphere.



One possible method for stabilizing the amount of carbon dioxide (CO_2) in the atmosphere is to inject it into the deep ocean, either from shore stations or from tankers at sea. (Reprinted courtesy of Lawrence Berkeley National Laboratory, Earth Sciences Division. Artist: Raine Reen.)

One approach being studied at Livermore is to sequester carbon dioxide—that is, capture the carbon and store it for long geologic time periods.

Carbon dioxide can be stored in several ways. For example, compressed carbon dioxide can be injected into geologic formations such as depleted oil and gas fields or saline aquifers (see *S&TR*, December 2000, pp. 20–22), or it can be injected into the oceans. Oceans absorb carbon dioxide naturally in ongoing processes that are very slow. However, the oceans' capacity for carbon dioxide is quite large. They already take up one-third of the carbon emitted by human activity, which is about 2 billion metric tons each year.

In July 1999, the Department of Energy established the Ocean Carbon Sequestration Research Program to investigate the feasibility, effectiveness, and environmental acceptability of ocean carbon sequestration. "We evaluate the underlying science of various options," says atmospheric scientist Ken Caldeira, who leads the ocean carbon storage research at Livermore. "We look at the different proposals for increasing ocean carbon storage and present information to the policy makers who determine the nation's course of action in this area."

Caldeira is also leading the process to review ocean carbon storage options for the Intergovernmental Panel on Climate Change. This review will form the basis for international negotiations on the treatment of purposeful ocean carbon storage under the United Nations Framework Convention on Climate Change.

Sink It in the Ocean?

Two ocean carbon strategies are being considered. One is to inject carbon dioxide directly into the deep sea, and the other is to fertilize the ocean with iron, which will increase its uptake of atmospheric carbon dioxide.

Direct injection involves separating carbon dioxide from the flue gas produced by power plants, compressing and liquefying it, and then pumping it into the ocean. (See the figure at left.) If the injection site is deep enough, carbon dioxide will sink and perhaps form a "lake" at the bottom of the ocean. One concern about this approach, says Caldeira, is that the pH level of such a lake would make the deep ocean environment more acidic. However, the increased acidity will affect the ocean whether carbon is injected or remains in the atmosphere—it's just a matter of what part of the ocean will be most affected.

"If we continue consuming fossil fuels without doing anything at all," Caldeira says, "the ocean—particularly its upper layer—will become more acidic than it has been in millions of years. That change is bound to affect corals and other marine life near the surface of the ocean. By piping it down deep, we might protect this biosystem to some extent, but how the increased acidity will affect the lower depths of the ocean has yet to be determined."

The other major approach to ocean sequestration involves fertilizing the ocean with iron. Adding nutrients such as iron to the surface of the ocean can stimulate the growth of phytoplankton, which would take up additional carbon from the atmosphere as well. When these plants and the animals that eat them reach the end of their lifecycles and die, they—and the carbon inside them—would eventually drift down into the ocean's depths. Carbon dioxide from the atmosphere would then enter the surface ocean to replace some of the carbon that sinks.

But Will It Work?

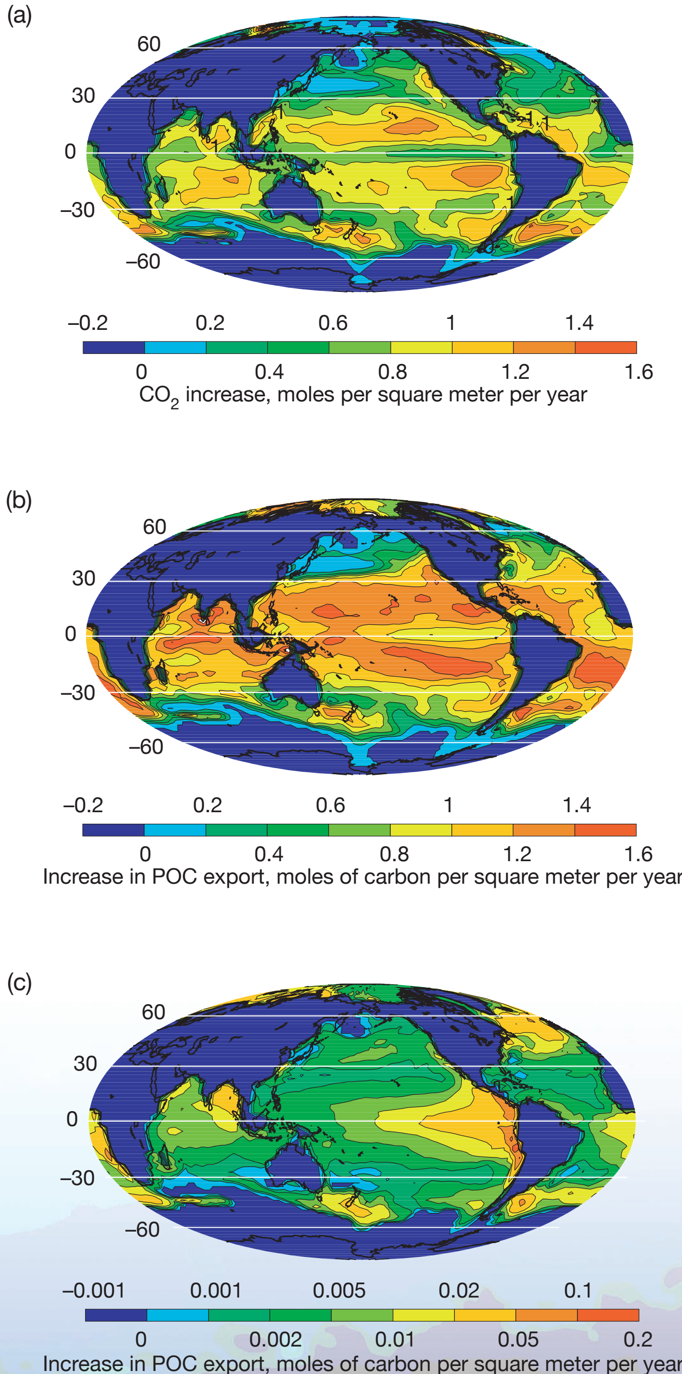
To evaluate the consequences and effectiveness of various options, Caldeira and his colleagues simulated different scenarios using the Livermore ocean general-circulation model. For example, simulations of iron fertilization of the oceans in the Southern Hemisphere initially showed that almost 8 billion tons of carbon would be absorbed by the ocean each year. Yet, after 500 years of continuous fertilization, the net increase in absorption would be less than 1 billion tons of carbon per year. (See the figure at right.)

Caldeira explains, "A couple of things happen to make this net absorption so low. First, the previously sequestered carbon dioxide does eventually leak back out of the ocean, although the leakage rate is most rapid in the first years." Carbon detritus that sinks to layers of constant density that are poorly ventilated to the atmosphere will stay in the ocean a long time.

Another issue arises with the bloom of marine plant life and the availability of other nutrients. "The models indicate that, eventually, other macronutrients become depleted even as we add iron," says Caldeira. "When that happens, the bloom falters, and the organisms are no longer taking up as much carbon as they did in the beginning."

Many unknowns remain, and much is yet to be worked out. "There are pros and cons to this approach," Caldeira says, "but it might be an effective low-cost technique, even with the leakage. Most living things would probably grow better, and the results could be monitored to avoid environmental surprises. However, at best, it's only a partial solution to the problem, and it would involve ecosystem management on an unprecedented scale."

The team also examined different facets of the direct injection technique and its variations using the same ocean model. Caldeira, Mike Wickett of the Center for Applied Scientific Computing, and Philip Duffy of the Climate and Carbon Cycle Modeling Group



Simulations of the iron fertilization process after 1 year show a dramatic increase in (a) the flux of carbon dioxide (CO_2) from the atmosphere to the ocean and (b) the sedimentary export of particulate organic carbon (POC) from the surface ocean. However, after 500 years, (c) POC export has greatly diminished.

used one-dimensional box-diffusion models and three-dimensional simulations to examine what happens over time when carbon dioxide is injected at different depths in the ocean. Injections were simulated at 800, 1,500, and 3,000 meters for 100 years near the Bay of Biscay, New York City, Rio de Janeiro, San Francisco, Tokyo, Jakarta, and Bombay. The team found that deeper injection led to longer sequestration, with the specific location of injection having less effect on sequestration time. Injection at a depth of 3,000 meters sequestered carbon from the atmosphere for several centuries, but shallower injections were less effective.

In a more recent project, Caldeira and Wickett simulated the direct injection of fossil-fuel carbon so they could assess the relative effectiveness of different injection sites and depths. Again, using the ocean general-circulation model, they injected carbon dioxide continuously at a rate of 0.1 million tons per year at 710 and 3,025 meters off the coasts of New York and San Francisco. At both sites, carbon escapes the ocean more slowly if it is injected more deeply. The highest fluxes of injected carbon escaping the ocean occur far from the injection site. For both the shallow and deep injection depths, carbon escapes the ocean more slowly for the San Francisco site than for the New York site.

The specific whys and wherefores of these results have much to do with circulation systems of the different oceans as well as the viscosity, salinity, and density of the ocean water at various depths and locations. For instance, the simulations showed that large-scale advective processes may be more important in bringing deep water to the surface in the Atlantic basin than in the Pacific basin, so carbon escapes more readily from the New York site.

In another project using the same model, Caldeira and Wickett compared the changes in pH when carbon dioxide is injected into the ocean and released to the atmosphere. They simulated the release of 7 petagrams of carbon annually (1 petagram is 1 billion metric tons or 1,000 billion kilograms) for 1,000 years into the atmosphere and into the ocean at 3 kilometers. They found that, whether carbon dioxide is released to the atmosphere or in the ocean, eventually, about 80 percent of it ends up in the ocean in a form that will make the ocean more acidic. However, with ocean injection, the problem of acidity is moved from the ocean surface to the deep. Previous studies showed that unless carbon dioxide is converted to some other form before injection, it will eventually make its way back into the atmosphere after diffusion or ocean circulation returns it to the ocean surface.

Limestone May Help

In research funded by Livermore's Laboratory Directed Research and Development Program, Livermore geochemist Kevin Knauss worked with Greg Rau of the University of California at Santa Cruz to address the pH problem. One solution may be to use common limestone in a technique called enhanced carbonate dissolution. This process involves hydrating carbon dioxide from power plant flue gas with water to produce a carbonic acid solution. The solution is then mixed with crushed limestone, which neutralizes the carbon dioxide by converting it to a calcium bicarbonate solution that can be released into the ocean. This process converts the carbon dioxide to a form that does not readily exchange with the atmosphere and that causes a less drastic change to the ocean's pH. The process occurs in nature through carbonate weathering, but at a much slower pace than envisioned in this enhanced version.

According to Rau, the carbonate dissolution process also might expand the capacity of the ocean to store carbon dioxide and minimize the amount of carbon escaping to the atmosphere. Another benefit is that the process would add calcium and bicarbonate to the ocean, which would enhance the growth of corals and other calcifying marine organisms.

Data for Deciding the Future

But what if no system is used to mitigate the release of carbon dioxide? Caldeira and Wickett also modeled the repercussions from that approach. The model incorporated historical and geologic data on carbon dioxide and emissions generated from the scenario set by the Intergovernmental Panel of Climate Change for the years 2000 to 2100. In addition, they explored the consequences of burning the remaining fossil-fuel resources during the next several centuries. The modeling results indicated that, unabated, carbon dioxide emissions over the coming centuries could produce changes in ocean pH that are greater than any experienced in the past 300 million years.

Caldeira adds that the research team is not responsible for making a policy decision. "Whether the decision is to do nothing, to do one thing, or to try a range of techniques, it is not our choice to make," he says. "Our role is not to be an advocate or back any particular options—one way or another. Our role is to provide the underlying science so that policy makers can make informed decisions."

—Ann Parker

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