Tracing the Role of Carbon Dioxide in Global Warming

The 1997 climate conference in Kyoto, Japan, was a milestone, not a culmination of climate science. Now, knowledge of the global climate system must be further developed to enable policies and mitigation measures for global warming. Carbon cycle modeling is one route to that knowledge.

As scientific debate continues over the causes, mechanisms, and extent of global warming, the nations of the world have begun acting on the plausible assumption that human activities, particularly the release of significant amounts of greenhouse gases into the atmosphere, are leading to global warming. While not conclusive, evidence has been mounting that human-induced climate change is occurring.

At the Kyoto climate conference in December 1997, policymakers, climate experts, and industrial leaders came together to seriously consider future global climate. Their goal: to negotiate limits on the future release into the atmosphere of carbon dioxide (CO_2), the most plentiful greenhouse gas, in order to prevent further human-driven climate change. The conferees took to heart the latest scientific findings on global climate processes that have resulted, in large part, from climate models.

Climate models are a major tool that scientists use to understand the complex web of climate mechanisms. However, important uncertainties remain. Scientists at Lawrence Livermore are actively seeking answers to the questions of how much climate is changing and how much CO_2 is stored naturally in the atmosphere and oceans, ultimately helping to resolve the larger uncertainty: what effect human activities have on our environment.

Climate modeling began in the 1960s, when the National Oceanic and Atmospheric Administration initiated development of general circulation models—complex mathematical descriptions of the physics and dynamics of the atmosphere and oceans. Since then, climate scientists here and elsewhere have been refining these models and formulating an entire hierarchy of other models to elucidate global climate. Their ultimate goal is a virtual global climate system, a model that will allow them to confidently predict future global and regional climate.

Development of such a model is far from complete. But with global climate change at the forefront of public attention and policymaking agendas, climate scientists must provide input to policymakers based on today's imperfect models while pressing forward to improve them. Indeed, they are working under some urgency, for the world now appears ready to take action against global warming.

One important question that models of the carbon cycle answer is what the future atmospheric concentrations of CO_2 may be. Carbon dioxide, a major greenhouse gas, is important to Earth's energy balance and climate. Because CO_2 concentrations have been increasing rapidly, climatologists have pinpointed CO_2 as a major cause of the increase in global temperatures observed since 1860, when complete temperature records began. It is no wonder, then, that the global carbon cycle has become a vigorous area of study for the Climate System Modeling Group in Lawrence Livermore's Earth and Environmental Sciences Directorate. (See *S&TR*, October 1996, pp. 6–13, for an overview of climate work in the Atmospheric Sciences Division, much of which stems from Livermore's multidisciplinary capabilities in scientific computation, nuclear testing, and atmospheric science.) The group also collaborates with Department of Energy sponsors and universities.

Determining Carbon's Fate

In nature, carbon is plentiful and dynamic. Its natural cycle is thought to have been in a relatively steady state for thousands of years until the industrial revolution. Then, humans perturbed the carbon cycle by clearing forests and burning fossil fuels (coal, oil, and natural gas), which increased the CO_2 content of the atmosphere. How has this anthropogenic change disrupted Earth's climate? To find out, scientists are obtaining a better understanding of how the climate system functions and tracking CO_2 released into the environment by humans.

Philip B. Duffy, group leader of the Climate System Modeling Group, says that their work includes modeling how a portion of anthropogenic CO_2 remains in the atmosphere and how the rest of it is taken up by the oceans and terrestrial ecosystems. Tracking CO_2 is neither simple nor easy: measurements of CO_2 in the ocean and terrestrial biosphere are scarce; CO_2 released by humans is indistinguishable from naturally occurring CO_2; and the natural fluxes of carbon between ocean, atmosphere, and terrestrial biosphere are poorly understood.

Lawrence Livermore modelers have been formulating and testing a suite of models to reproduce carbon absorption, transport, and storage processes. The models cannot possibly incorporate all climate factors everywhere—even Livermore's advanced supercomputers cannot provide that resolution—so modelers must select the most important climatic factors and influences and represent them as well as possible.

The goal of the carbon cycle models is to predict the future behavior of carbon in the climate system. The models are tested by "hindcasting" the behavior of the carbon cycle from the historical past to the present. If model simulations match past records and observations, then model calculations predicting the future will merit confidence.

The Ocean Carbon Cycle

The Climate System Modeling Group's work involves both terrestrial and ocean carbon cycles, with current emphasis on the ocean. The ocean is an important regulator of climate as well as a major absorber of excess CO_2. Livermore modelers, having access to powerful, next-generation computers from the Department of Energy's Accelerated Strategic Computing Initiative, are able to formulate models that represent ocean currents, eddies, and interactive processes with more fidelity than previously possible. Their most recent ocean models reflect the advance of climate simulation techniques and skills. The projects described here demonstrate the approaches that modelers use to test hypotheses about carbon cycle dynamics, understand process interactions, and refine representations of the processes to derive accurate and useful models.

Improving Convection Models

The ocean is a large "sink" for anthropogenic CO_2. A model that can accurately simulate how the ocean absorbs anthropogenic CO_2 is prerequisite to predicting future atmospheric CO_2 concentrations and rates of global warming. But according to climate modelers Duffy and Ken Caldeira, current ocean models may overpredict the amounts of CO_2 that oceans absorb. One reason is that models do not accurately represent convection, the rapid vertical mixing of water that occurs when dense water overlies less dense water. They saw the

effects of that inaccuracy in models involving sea-ice formation, which is a major cause of ocean convection.

When sea ice is forming, it expels salt into surrounding surface water. The saltier, denser water triggers convection, sinking the surface water and CO_2 it contains into the depths of the ocean. Surface ocean concentrations of CO_2 are thus reduced, and more CO_2 transfers from the air to the sea.

In the real ocean, convection occurs in horizontal regions that are meters or hundreds of meters across. Because ocean models cannot accurately represent such small features, some significant inaccuracies can arise in their simulations. Duffy and Caldeira thought that the modeled transfer of CO_2 from air to sea was probably too great because the models simulated excessive convection. If the instabilities resulting from expelled salt were treated more carefully, model results might better represent reality.

The two modelers tested their hypothesis by performing a pair of simulations that compared the standard treatment of convection to a "test" simulation in which the model's convection mechanism was partially suppressed. In the standard "control" simulation, salt released during sea-ice formation is placed in the model's top layer (which is 25 meters thick), and the model's convection mechanism mixes it into the rest of the ocean. Because the convection mechanism is clumsy, excessive convection occurs. This in turn causes excessive ocean absorption of carbon.

In their test simulation, Duffy and Caldeira dispersed expelled salt uniformly over a broader area—from the surface down to a depth of 160 meters—and suppressed the model's convection mechanism (Figure 1). This simulation produced much more realistic results for simulated convection, salinity, circulation, and absorption of chlorofluorocarbons (CFCs).

Then CFC uptake was simulated as an indirect test of the model's ability to simulate ocean uptake of anthropogenic CO_2. No direct method is possible because anthropogenic CO_2 cannot be reliably distinguished from natural CO_2 in the ocean. By contrast, CFCs have no natural background concentration in the ocean. Moreover, CFC uptake is very closely related to the ocean's absorption of human-induced CO_2, as Figure 2 shows.

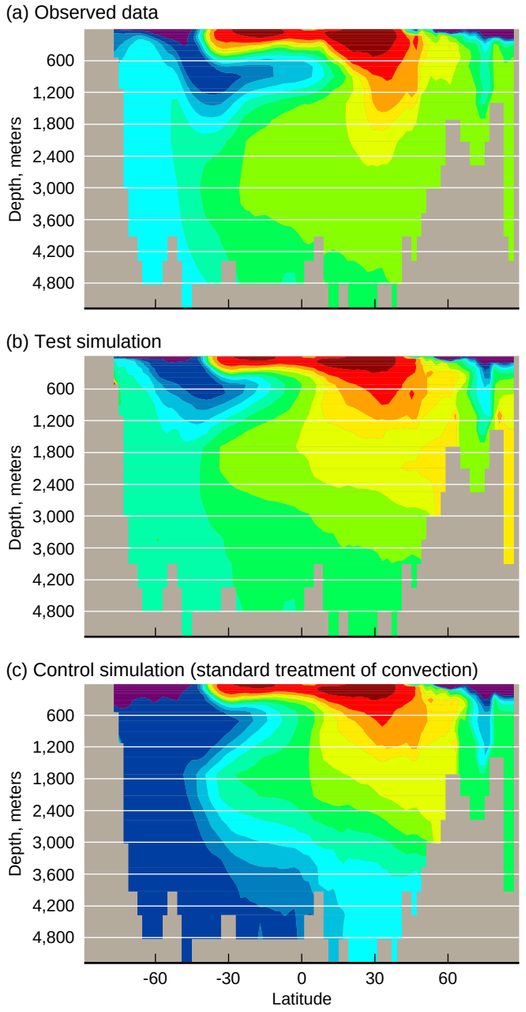

Figure 1. Salinity from (a) observed data collected in the Atlantic Ocean is compared to Livermore (b) test and (c) control simulations. The test simulation's more realistic portrayal of ocean convection is one of several improvements to Livermore's ocean circulation and carbon cycle model.

Because of this close relationship, Caldeira and Duffy reasoned that the standard model treatment of ice formation, which results in excessive simulated ocean uptake of CFC, also produces excessive uptake of anthropogenic CO_2. In addition, the improved treatment of ice formation, which produces greatly improved simulated uptake of CFCs, should also produce more accurate calculations of the uptake of anthropogenic CO_2. Further simulations are planned to verify these results.

Modeling Marine-Biology Effects

Marine biological processes play a large role in ocean carbon cycle dynamics, but they have been incorporated only recently into climate models. The inherent difficulties of mathematically describing their spatial and temporal effects have been a challenge. As a result of inadequate modeling of these processes, climate scientists have not been able to study the influences of marine biology and feedback responses to them. They have not known how the processes would affect the ocean carbon cycle.

Caldeira has a project under way to investigate some of these processes and clarify some of the uncertainties surrounding ocean and marine-biology interactions. He is using recently collected remote sensing and satellite data to model the interplay between sunlight, plankton (barely moving plant and animal aquatic organisms), and the ocean's absorption of CO_2.

Earlier models have established connections among solar radiation, plankton, and ocean circulation dynamics. With newly available data, Caldeira is studying these intertwinings further, considering feedback interactions in the process. For example, when sunlight penetrates the ocean layers and heats the deeper waters, convective mixing results and causes two other effects. First, CO_2 in the surface waters downwells and must be replaced by CO_2 transferred from the air to the sea; second, nutrients from the depths well up to the surface. Additional nutrients increase plankton growth. In time, the increased volume of plankton blocks solar penetration, so the sunlight heats only the surface waters. This inhibits CO_2 downwelling, nutrient transport to the surface, and plankton growth. Does the ocean then return to its steady state, or does the cycle continue through other ecosystem dynamics? And what is the cumulative effect on the ocean's absorption of CO_2?

Caldeira's study will systematically simulate the interactions among solar radiation, plankton, and ocean dynamics; the feedback resulting from those interactions; and the impacts of the feedback on the predicted response of the ocean carbon cycle to climate change. The simulations will replicate the time frame from the preindustrial ocean carbon cycle (before 1765) to the present. The simulations will also calculate future atmospheric CO_2 content based on several emission scenarios that may result when CO_2 stabilization policies are implemented.

CO_2 by Radiocarbon Proxy

Radiocarbon, or ^{14}C, has provided much of our knowledge about the rates of carbon exchange from the atmosphere to the oceans and land, and it yields

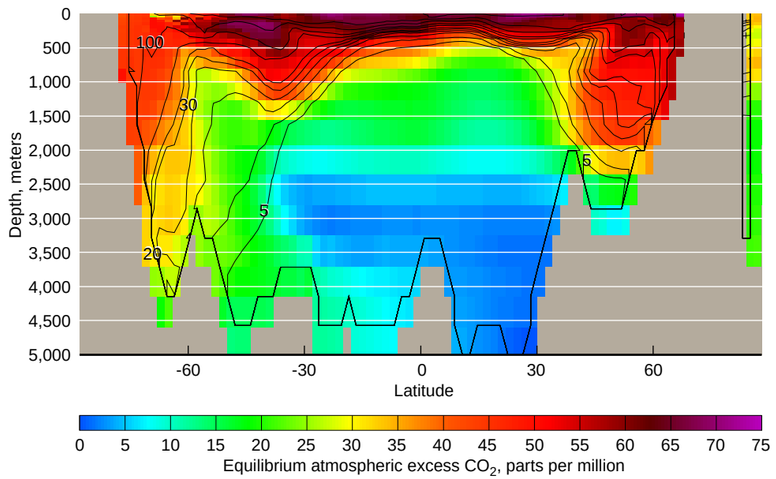

Figure 2. Livermore climate modelers performed simulations of chlorofluorocarbons (CFCs, shown as contour lines) and CO_2 (colored areas) to demonstrate their similarities in distribution in ocean waters. The similarities between ocean distributions of CFCs and anthropogenic CO_2 mean that model simulations of CFCs are a good indirect test of their ability to simulate anthropogenic CO_2.

important information about the ocean circulation. The radioactive half-life (5,730 years) of ^{14}C is comparable to the time span taken by surface ocean water to circulate to the ocean bottom and back. This means that the spatial distribution of ^{14}C in the water yields significant knowledge about ocean circulation—water that has not been near the surface recently has significantly lower ^{14}C concentrations because of radioactive decay.

For climate modelers, data on ^{14}C distributions took on additional usefulness as a result of the atmospheric nuclear tests conducted mostly in the period from 1954 through 1963. The concentration of ^{14}C in atmospheric CO_2, which had remained fairly constant for the previous thousand years, was doubled by those nuclear tests in less than 10 years. Since the end of the tests, ^{14}C concentrations have been decreasing as atmospheric CO_2 moves into other carbon reservoirs. This infiltration of nuclear-testing ^{14}C into carbon reservoirs can provide valuable information on carbon exchange. In particular, if the rate of nuclear-testing ^{14}C transfer from the atmosphere to the oceans and land could be accurately predicted, climate scientists would be able to predict the rate at which the oceans and land absorb human-induced CO_2 because essentially the same physical rules govern the transfer processes. Thus, understanding ^{14}C transfer is another route to determining rates of future greenhouse warming.

Models to simulate this transfer process make use of the estimated amounts of ^{14}C created by nuclear tests; they also make use of nuclear-testing ^{14}C data that were actually measured in the troposphere and stratosphere. If the models are accurate, the total amount of nuclear-testing ^{14}C transferred to the oceans, land, troposphere, and stratosphere should equal the estimated inventory of nuclear-testing ^{14}C, and the amounts transferred to the troposphere and stratosphere should approximate the measured data.

Early models simulating this transfer matched observed data only in part. In 1995, Duffy, five collaborators from Lawrence Livermore, and one from the University of Illinois tackled the problem of transfer. They used different and relatively more sophisticated multidimensional models of the ocean, stratosphere, and land, which they ran using observed data on tropospheric concentrations of ^{14}C as the model boundary conditions. Their simulations, for the period from 1955 through 1990 (Figure 3) are well within previously recognized uncertainties. This exercise proved that contemporary models can accurately account for all the bomb-produced ^{14}C in the climate system.

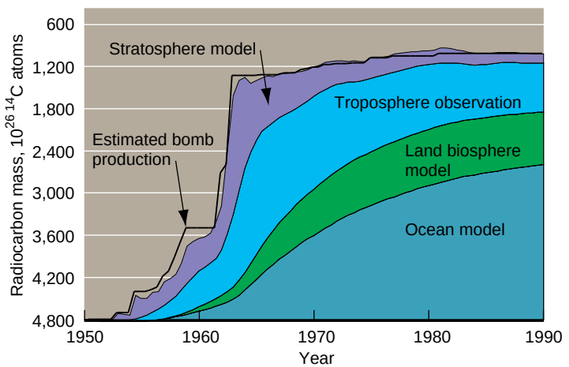

Figure 3. The Livermore-modeled estimates of nuclear-test radiocarbon in the ocean, land, and atmosphere closely match estimates of the total radiocarbon inventory calculated from atmospheric tests.

Radiocarbon by Salmon Proxy

To validate models of how the ocean absorbs nuclear-testing ^{14}C, modelers must be able to distinguish between how much of the total ^{14}C now in the ocean is bomb-produced and how much is natural. The modelers therefore need to know the natural ^{14}C concentrations before the weapons tests and how quickly the ^{14}C entered the oceans. The problem is that few open-ocean measurements of that period have been taken.

Tom Brown of Livermore's Center for Accelerator Mass Spectrometry, working with the Livermore ocean modelers and ocean and fishery scientists from the University of Washington, came up with a way to provide the "pre-bomb" ^{14}C data. In 1997, they measured the ^{14}C content of archived salmon scales using Livermore's accelerator mass spectrometry capability (see *S&TR*, November 1997, pp. 4–11), which can measure minute isotopic quantities with high precision. The salmon-scale measurements are proxy indicators for the ^{14}C levels, and even the ^{13}C-to-^{12}C ratios, of the surface waters of the oceans during the time period the salmon dwelled in the waters.

Fishery scientists have been collecting and archiving salmon scales for nearly a hundred years for various research purposes. The scales are particularly suitable for developing time-history data of ocean waters because the salmon's seasonal migration patterns are known. And because salmon live and feed on plankton and small fishes in the uppermost surface waters of the ocean, the scales can be equilibrated with the ^{14}C content of the surface waters. Furthermore, the sections of the scales that grow while salmon live in the open ocean are identifiable—they appear as bands of different thickness roughly corresponding to seasons (Figure 4).

By selecting and measuring appropriate sections of the scales, Brown obtained estimates of ^{14}C content of North Pacific surface waters, averaged over the very large areas of the salmon's seasonal migration patterns and over the 1- to 2-year time spans represented by the sections. The ^{14}C measurements show excellent agreement with the few direct, open-ocean measurements available of ^{14}C content and clearly show the rise in ^{14}C content from the atmospheric nuclear tests (Figure 5). By providing rare estimates of "prebomb" values and the initial increase of ocean ^{14}C concentrations, Brown's measurements are a valuable help to climate scientists trying to predict future uptake of CO_2 by the ocean as well as future climate.

Fossil Fuel Affects ^{14}C Fluxes

Burning fossil fuel may appear to have no effect on atmospheric radiocarbon content because fossil fuel contains no ^{14}C. However, global processes are rarely that simple or linear. Caldeira and Duffy collaborated with Greg Rau from the University of California at Santa Cruz to formulate a model to quantify radiocarbon fluxes. Their model predicted significant, though indirect, effects of fossil-fuel burning on global distributions of ^{14}C. More important, if its prediction of increased ^{14}C levels by 1998 is correct, this model will soon become a test for global carbon-cycle models.

The model's calculations of changes induced by land clearing, fossil-fuel burning, and atmospheric nuclear tests show that, in the very near future, ^{14}C in the atmosphere will begin to increase. Even though ^{14}C, which increased between 1954 and 1963, has been steadily declining, that decline will be reversed if humans do not change their habits in burning fossil fuel.

Caldeira, Duffy, and Rau used a simplified model of the atmosphere, land, and ocean. The model—driven by carbon fluxes from land clearing, fossil-fuel burning, and atmospheric nuclear tests—was used to simulate changes that would occur in the face of isotope decay, continuing CO_2 emissions, radiocarbon exchanges into the oceans and atmosphere, and estimates of future biomass. Nuclear test radiocarbon inventory in 1975, as well as data on both natural and bomb radiocarbon collected through GEOSECS (Geochemical Ocean Sections Study, an ocean data collection

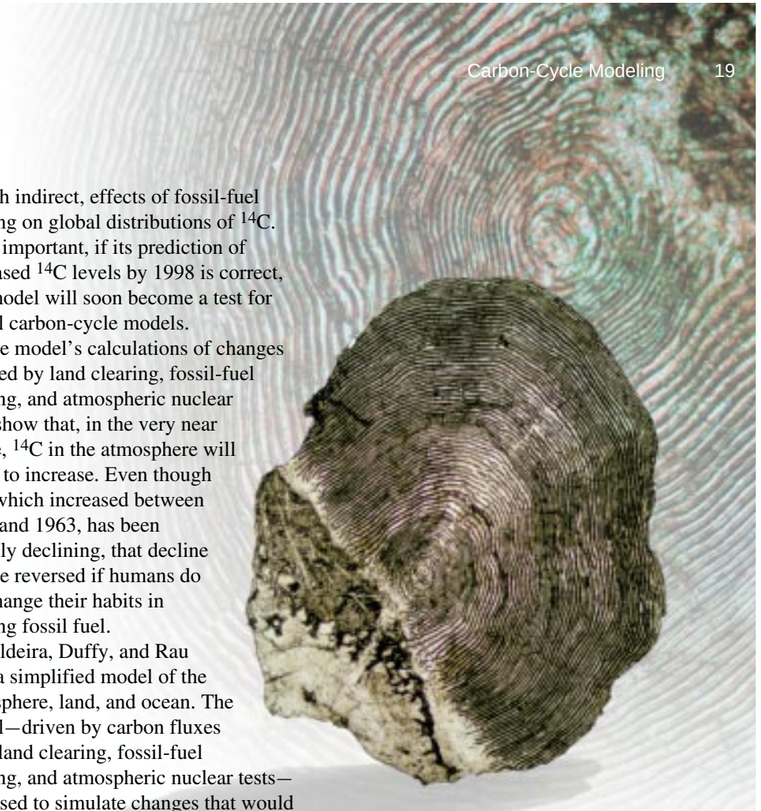

Figure 4. Bands on an archived salmon scale (about 5 millimeters wide) give age and radiocarbon content with the help of Livermore's Center for Accelerator Mass Spectrometry.

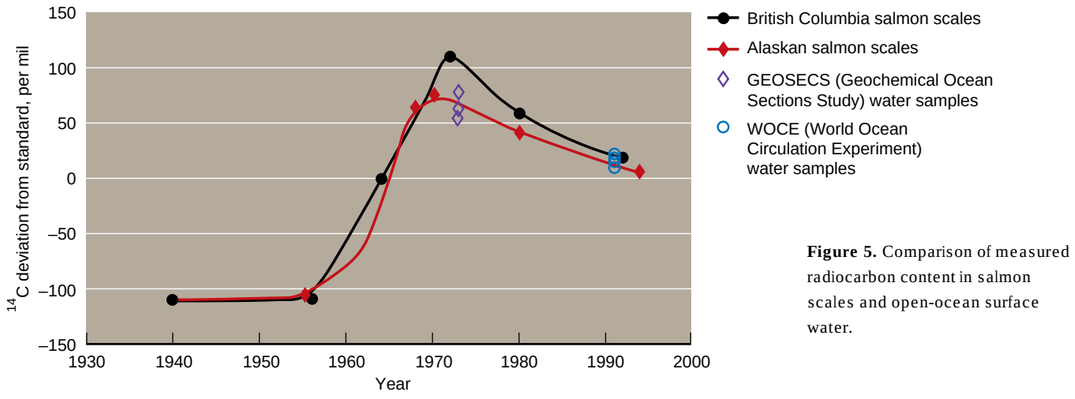

Figure 5. Comparison of measured radiocarbon content in salmon scales and open-ocean surface water.

program), were used as reference points for adjusting model parameters.

Simulations were performed to separately assess the changes caused by (1) land clearing and fossil-fuel burning, (2) land clearing only, (3) fossil-fuel burning only, and (4) both plus observed atmospheric data until 1990, which includes nuclear-testing ^{14}C levels. The last simulation indicates the model's ability to portray past trends and predict future ^{14}C fluxes.

The simulations indicate what percentages of increases in atmospheric CO_2 can be attributed to deforestation and fossil-fuel burning. The data indicate that, prior to about 1910, most of the carbon entering the ocean resulted from deforestation; since that date, the carbon flux has been dominated by the effects of fossil-fuel burning.

The modelers' interpretation of the trends led them to the unexpected prediction that ^{14}C levels in the atmosphere will begin to increase as a result of fossil-fuel burning. The modelers explain it this way: When atmospheric CO_2 content increases, the ocean's absorption of it increases. In the case of fossil-fuel-caused increases, because fossil fuel contains no radiocarbon, the ocean is absorbing CO_2 that consists primarily of ^{12}C, a weak acid. A more acidic ocean tends to reject carbon in all its isotopic forms. So the ^{14}C component of ocean CO_2 is rejected along with the other carbon isotopes, adding to the atmospheric ^{14}C content and reversing the decline that began in the 1960s after the end of atmospheric testing. The model indicates that ^{14}C levels will begin increasing as early as 1998 and, by 2015, the fossil-fuel-induced radiocarbon flux out of the ocean will exceed the nuclear-explosion radiocarbon flux into the ocean, so the ocean's ^{14}C mass will then begin to diminish.

The Caldeira, Duffy, and Rau model is noteworthy because the prediction that the ^{14}C flux into the ocean will be reversed early in the next century indicates that human impacts on the global carbon cycle are significant on geologic, not just human, time scales.

Closing In on Global Climate

The growing consensus that fossil-fuel use is causing climate change and the recent effort to formulate international treaties to limit greenhouse-gas emissions lend urgency to understanding how carbon moves within the climate system. If indeed humans have been responsible for changing the climate, climate models must accurately and conclusively portray this cause and effect. Then we will have the understanding needed to begin mitigating the effects and assuring a better future for the environment.

—Gloria Wilt

Key Words: carbon cycle, carbon dioxide (CO_2), climate change, climate model, fossil-fuel burning, global warming, greenhouse gas, marine biology, mass spectrometry, ocean carbon cycle, ocean convection, proxy data, radiocarbon (^{14}C).

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About the Scientists

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KENNETH G. CALDEIRA joined the Laboratory's Atmospheric Chemistry Group as a physicist in 1993 and has been an environmental scientist in the Climate System Modeling Group since 1995. He received his Ph.D. and M.S. in atmospheric science from New York University in 1991 and 1988 and his B.A. in philosophy from Rutgers University in 1978. He also served as a postdoc at Pennsylvania State University's Earth System Science Center. Caldeira has published many papers, for example, on climate stability of early Earth and the global carbon cycle as it has been affected by human activity over millions of years.

Reliable Software for Protection Systems

A patient undergoing radiation therapy for cancer wants to be sure that the radiation being delivered is just the amount prescribed and no more. Nuclear power plants must have systems installed to ensure that radiation leaks and accidents do not occur. Today, controlling these protection systems flawlessly depends upon computer software, which occasionally contains unforeseen "bugs." Software bugs on your computer at home are annoying, but at a nuclear power plant or during radiation therapy they can be life-threatening.

At Lawrence Livermore, Gary Johnson's Computer Safety and Reliability Group—part of the Fission Energy and Systems Safety Program—has been working with the Nuclear Regulatory Commission for several years to avoid software problems in safety systems at nuclear power plants. Livermore brings to this job decades of systems engineering experience as well as a regulatory perspective from years of working with the NRC and other regulators.

Johnson's group and the NRC developed software and computer system design guidance that the NRC uses to evaluate the design of safety-critical systems for U.S. plant retrofits. Overseas, where new nuclear power plants are being built, regulators and designers are using this state-of-the-art guidance to help assure plant safety. For the last few years, representatives from Hungary, the Czech Republic, Ukraine, Korea, Taiwan, and Japan have been calling upon Johnson and his group for assistance in setting criteria for their nuclear power plant control systems.

This software design guidance is also applicable to other computer-controlled systems that could endanger human life if they are poorly designed—medical radiation machines, aircraft flight control systems, and railroad signals, for example.

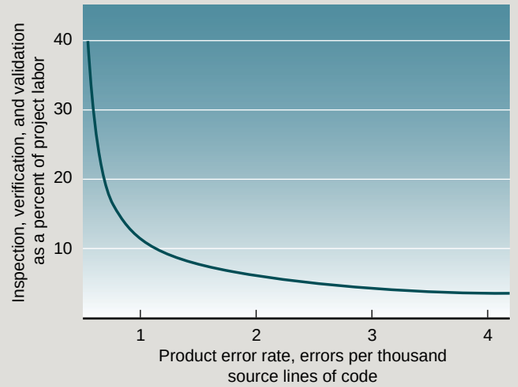

Figure 1. Data from IBM's Federal Systems Division indicate that when more effort is spent up front for inspection, verification, and validation, the product error rate decreases.

When Software Fails

Perhaps the best-documented example of the harm resulting from poorly designed software involved the Therac-25, an accelerator used in medical radiation therapy. The *IEEE Computer Applications in Power* reported, "Between June 1985 and January 1987, six known accidents involved massive overdoses by the Therac-25—with resultant deaths and serious injuries" at treatment centers around the U.S. and in Canada.[1] Between the patient and the Therac-25's radiation beam was a turntable that could position a window or an x-ray-mode target between the accelerator and patient, depending on which of two modes of operation was being used. If the window was positioned in the beam's path with the machine set to deliver radiation through the x-ray-mode target, disaster could result because software errors allowed the machine to operate in this configuration.

Engineering Reliable Software

Conditions such as these, where software was assigned sole responsibility for safety systems and where a single software error or software-engineering error could have catastrophic results, are precisely what Johnson's group aimed to avoid when it helped to prepare the portion of the NRC's recently published *Standard Review Plan*[2] regarding computer-based safety systems. Their process requires that software for nuclear power plant protection systems be written in accordance with good engineering practices. That is, software should follow a step-by-step approach of planning, defining requirements for worst-case scenarios, designing the software, and following a detailed inspection and testing program—