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money for the federal government immediately, and be more than paid back in a few years or sooner."

On 17 April, President Bush ordered each federal agency to develop and implement a plan to reduce its overall energy use in buildings by 20% from 1985 energy use levels "to the extent that these measures minimize life cycle costs and are cost-effective." All new federal buildings must meet energy performance standards, and agencies must reduce their motor vehicle fuel consumptions by at least 10% in 1995 from 1991 levels. A "maximum number practicable" of alternative fueled vehicles must be purchased by agencies each year.

Copies of the OTA report, *Energy Efficiency in the Federal Government: Government By Good Example?* are available for US $5 from the Superintendent of Documents, USGPO, Washington, DC 20402-9325. Tel: +1-202-783-3238. Reference GPO Stock Number 052-003-01242-1.

Science Update

Researchers Protest Their Inclusion in Skeptics' Agenda

On page 1 of *Global Climatic Change: A New Vision for the 1990s*, the US greenhouse skeptics' alternative research agenda (see *GECR*, 1 March, pp. 1-3), one finds the following statement: "The consensus of the scientists in this research prospectus is that there is considerable evidence that the impact of future climatic change may be neutral or even beneficial."

But to at least three of the scientists whose proposals were included in the agenda, that claim is misleading. According to one of them, there was no formal consensus reached or even called for at the meeting which produced the agenda, nor was the introduction to the research agenda circulated among the participants for their approval. Finally, at least four of the researchers listed were not even invited to the meeting, did not know their proposals were being included, and were unaware that their names would appear in the prospectus.

On 6 May, *GECR* received a letter from David Robinson of Rutgers University, urging us to print a clarification. Robinson, who was listed on a project proposal as a co-investigator with George Kukla of the Lamont-Doherty Geophysical Observatory, was not invited to the meeting and didn't hear about the research agenda until he read about it in *GECR*. Andrew Lacis of NASA Goddard, who was listed in the same proposal as co-investigator, hadn't heard of the meeting or the research agenda until *GECR* telephoned him on 13 May. Both Kukla and Robinson strongly objected to the "consensus" wording in the prospectus; Robinson has written to Patrick Michaels and Robert Balling (the organizers of the meeting and the authors of the prospectus' introduction) to ask that the language be revised.

Balling told *GECR* that he and Michaels are polling all of the scientists named in the prospectus and will prepare a statement on the actual level of consensus within the group. Balling says that he and Michaels *did* circulate the agenda's introduction to the conference attendees prior to publication, but Kukla denies having seen it. As for the researchers who weren't invited to the meeting, Balling points out that all of them were co-investigators. He says it was the responsibility of the principal investigators who attended the meeting to notify their co-investigators that their names would be included in the prospectus.

Ice Ages and Plankton Don't Mix

As Paul Colinvaux pointed out in his classic 1978 primer on ecology, *Why Big Fierce Animals Are Rare*, most of the world's ocean is a desert. Nutrients are scarce, as are the plants and animals that require them. Of course, coastal areas and regions of upwelling are more productive, but they account for only 10.1% of the ocean's surface. The rest, as Colinvaux says, is "a blue desert more useless to life than most of Arabia." The Antarctic ocean, however, is the most enigmatic exception to that sweeping statement. Nutrients are abundant there, and yet phytoplankton are comparatively scarce. Because of the Antarctic's great unrealized potential for biotic activity, scientists have looked to it as a potential modifier of CO_2 concentrations under different climate regimes — hence the proposals for iron fertilization and the widely accepted theory that a phytoplankton bloom in the Antarctic ocean caused global CO_2 concentrations to drop during the last ice age.

These ideas, however, are set spinning by a new study reported in the 16 May issue of *Nature* (vol. 351, pp. 220-222). R.A. Mortlock and colleagues from Lamont-Doherty and Columbia University (Palisades, New York) use three lines of evidence to show that phytoplankton productivity was in fact low, not high, during the last ice age, and the plants were less efficient at taking up nutrients. Mortlock et al. analyzed records of the accumulation rates of diatom shells, the ratio of germanium to silicon in opal (also related to diatom production), and the carbon isotope ratio in the shells of foraminifera to reach their conclusions. As W.H. Berger of Scripps Institution of Oceanography points out in an accompanying article on pp. 191-192, this analysis should "severely damage conventional belief in Antarctic modulation of atmospheric carbon dioxide." However, Berger says the question is still not totally resolved, since there could be alternative explanations for some of Mortlock's findings.

Technologies Reduce Societies' Vulnerability to Climate

In the 25 April issue of *Nature* (vol. 350, pp. 649-652), Jesse Ausubel of The Rockefeller University in New York discusses evidence that technology has allowed human societies to become increasingly shielded from the effects of climate and weather. Ausubel argues convincingly that there is a trend toward systems that are less vulnerable to climate, citing examples ranging from food preservatives to weather satellites. "In many respects we seem to be 'climate-proofing' society," Ausubel says. Even agriculture may be more robust than many people think: transportation systems allow people to rely on food sources outside their area and thus "spread production risks across more climatic zones," and existing crop cultivars in the US are generally replaced by new ones within just eight to nine years.

Ausubel points out that the adaptations for long-term climatic change will probably resemble those for other climate variations — those that "mollify the difference between daytime and nighttime temperatures, protect against normal variability between days, shield from storms and hail, adjust to the seasons, and adapt to the wide range of climates where people already live."

Ausubel points to the steady improvements in technological performance and efficiency, suggesting that this trend will continue and that human vulnerability to climate will keep declining. (Readers should keep in mind *GECR*'s 15 March Focus Report on the potential vulnerability of nonfossil energy systems to climate, however. One should also note that Ausubel's analysis is based on industrialized countries.) Ausubel notes that ecosystem vulnerability is another question entirely, and does not suggest overtly that climate change is nothing to worry about, but he implies that "business as usual" may yield a more favorable future for humanity than many have suggested.

Reforestation in the Northern Hemisphere: The Missing Sink?

According to an article in the 4 May issue of *New Scientist*, the spread of forests in the Northern Hemisphere could account for much of the missing sink for carbon. Roger Sedjo of the Washington-based Resources for the Future used forestation data from the UN Food and Agriculture Organization to conclude that 700 million metric tons of carbon are being captured in Northern Hemisphere trees and soils each year.

Sedjo presented his paper at this year's annual meeting of the American Association for the Advancement of Science. A second unpublished paper by Sedjo, which considers the effect of tropical deforestation, concludes that while the destruction of tropical forests adds 2 billion tons of carbon into the atmosphere, much of that will be reabsorbed while the forests grow. Sedjo says the net emission of carbon from tropical deforestation is 700 million tons, coincidentally the same amount that's being absorbed by Northern Hemisphere forests. Last year, Taro Takahashi and Pieter Tans reported in *Science* that oceans absorb only at most one billion tons of carbon, and there must be a large terrestrial sink (*GECR*, 9 March 1990, p. 5). Sedjo's findings could explain "a large amount" of the missing sink.

Sedjo told *GECR* that his analysis "flies in the face of the conventional wisdom" that Northern temperate forests are in balance with regard to CO_2.

Upgrade on NIST Refrigerant Mixtures Database Available

The US National Institute of Standards and Technology (NIST) has released an update to its Thermodynamic Properties of Refrigerants and Refrigerant Mixtures Database. The database, which will run on any AT- or XT-class personal computer (and requires 512 K of memory) allows researchers to produce tables of thermodynamic properties of 18 pure refrigerants, including ethane-based compounds, and 24 mixtures. Mixtures of up to five components can be analyzed.

The upgrade contains new data on mixing parameters for four blends (including HCFC-22 and HFC-152a), and has revised Carnahan-Starling-DeSantis coefficients for all 18 refrigerants.

Version 2.0 of the REFPROP database is available for US $340 from the Standards Reference Data Program, A320 Physics Building, NIST, Gaithersburg, MD 20899, USA. Tel: +1-301-975-2208; Fax: +1-301-926-0416. Upgrading to version 2.0 from 1.0 costs $90.

New Climate Journal Calls for Papers

Climate Research, subtitled Interactions of Climate with Organisms, Ecosystems, and Human Societies, has issued a call for papers. The new journal is published by Inter-Research in Germany, and appears to be in the same league as *Climatic Change* and *Global Environmental Change: Human and Policy Dimensions*.

Climate Research invites papers on interactions of climate with organisms, populations, ecosystems, and human societies; short- and long-term changes in climatic elements; methodological aspects of

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May 7, 1991

Discover Magazine
3 Park Avenue
New York, N.Y. 10016

To the Editor:

John Martin proposes iron fertilization of the Southern Ocean as at least a partial solution to the threat of global warming. ("Earth On Ice", April 1991). In my opinion, he's got it exactly wrong. Our manhandling of the global environment created the problems we face; it is not part of the solution.

It would be easy to attack Martin's suggestion on technical grounds: there is evidence that iron is not the limiting nutrient in the oceans; very recent research shows that, even if adding iron would increase plankton populations, the net amount of carbon sequestered would be modest; massive amounts of money and other resources would have to be mustered if the program were to be even marginally successful in achieving its objectives.

But my opposition to Martin's suggestion runs much deeper. The proposal is dangerous because it plays to wishful thinking that there is no need for fundamental change in the design of our civilization; and that, with a little creative engineering, we can out-smart nature once again. The truth, however, is that we cannot, without serious repercussions, continue our hubristic campaign of re-creating the environment.

You would think we would have learned that lesson by now. This is certainly not the first time we have undertaken such technological "fixes". Our determination to produce crops in areas not suited to produce them, for example, has poisoned the soil and, in some areas, created vast deserts of salt and pesticides. And consider our desire to adorn ourselves cheaply in silk by bringing gypsy moths into the country -- vast stands of diseased and dying trees are the legacy of that venture. The kudzu vine that chokes native plants and trees in the Southeast; the rabbits that overran Australia; and the Africanized bees that have now made their way into the United States, are all testimony to our inability to gauge and control the effects of grand eco-engineering schemes. And those are nothing compared to this proposal.

It is time we stop kidding ourselves. The simple truth is that it is only by changing our behavior -- and our relationship to the earth -- that we can effectively address the global environmental problems we face. Study after study tells us we can make make significant gains at minimal cost with existing technologies. The need for such action is clear. The ozone layer is being depleted at an alarming rate; we need to move quickly to end the use of ozone destroying chemicals. We continue to experience record warmth, severe drought, extensive forest fires, and other warning signals consistent with those long since predicted to accompany the onset of global warming and climate change; we need to cut our emissions of greenhouse gases in every sector of the economy. The very threads of the web of life are being severed as rampant deforestation drives thousands of species to extinction; we need to preserve and protect sensitive ecosystems and manage our forests sustainably.

So let's get on with it. I challenge our scientists to use their insights and creativity to devise ways for us to live in harmony with nature -- rather than speeding us further along on the collision course we are currently travelling.

Sincerely,

Al Gore

Al Gore
United States Senator
Chairman, Senate Subcommittee on
Science, Technology, and Space

Will send
thanks

DISCOVER

March 21, 1991

The Honorable Al Gore
United States Senate
393 Russell Senate Building
Washington, DC 20510

Dear Senator Gore:

Enclosed is the most recent issue of DISCOVER. It contains the article ''Earth on Ice'' on page 54, which we thought might interest you. On our letters page we like to encourage an exchange of views about our articles. We'd be happy to consider any letter that you might want to write.

Thank you for your time.

Sincerely,

Betsy Hanson
Clarence V. Reynolds

Betsy Hanson
Clarence V. Reynolds
Researchers/Reporters

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WASHINGTON, DC 20510-4202

April 16, 1991

Discover
3 Park Avenue
New York, N.Y. 10016

To the Editor:

Responding to your article "Earth on Ice" (April 1991), I must express my concerns regarding the iron fertilization of phytoplankton in the Antarctic as a means of lowering atmospheric CO2 levels. The concept of iron fertilization as a "fix-it" for reversing the greenhouse effect begs the issue, and proposes a simplistic solution to a very real and complex problem. Certainly the concept may be embraced as a means of conducting business as usual, but presenting iron fertilization as a panacea for this global problem is misleading.

The concept of iron fertilization in the Antarctic has generated critical research and discussion that question the plausibility and desirability of adopting such a proposal. Most notable is Peng and Broecker's (1991) research on ocean dynamics that concludes negligible to insignificant lowering of atmospheric CO2 by iron fertilization after 100 years of totally successful fertilization. Their results suggest that with a "business-as-usual" scenario of fossil fuel CO2 emissions in the next century, the CO2 content of the atmosphere would be lowered by only about 5-15% below what it would have been without fertilization.

What are the costs of this concept? As you mention in the article, the costs of testing the iron fertilization of a small 60 mile x 60 mile square of ocean would run between the tens of millions of dollars and more than a hundred million. Once begun, the fertilization process would require even, annual dispersal of iron for at least 100 years to ensure the retention of carbon. The fertlization process would involve the use of hundreds of barges and ships, their transport and upkeep, the purchase of soluable iron, and the payment of labor -- at an estimate in the billions of dollars (Borchelt 1990). Given the annual costs of such an operation over a 100 year period, would a lowering of atmospheric CO2 levels by 5-15% be worth it?

Furthermore, the environmental costs of the iron fertilization concept need to be fully explored and weighed. Many scientists are concerned that the long-term ecological effects of iron fertilization may be devastating. For example, successful fertilization would increase the amount of organic material in the deep ocean water. In the worst case scenario, reoxidation of these organic materials would diminish the supply of oxygen in the Antarctic deep water to the point of anoxic condition. Repercussions would include the loss of krill

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eggs and krill upon which whales, seals, squid, fish, and penguins feed. Such a loss of oxygen in the deep ocean would liken the area to a devastated and less productive lake environment.

The concept of iron fertilization focuses our attention on short term "fix-it" approaches in dealing with the greenhouse effect rather than on changing the attitudes and behaviors that produce CO_2 emissions in the first place. If we expended as much money, time, and energy that the iron fertilization scheme proposes over the next 100 years into reducing the primary production of CO_2 emissions, the problem would be solved -- or, at least, substantially reduced.

Sincerely,

Al Gore
U.S. Senator

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EARTH ON ICE

A Bold Attack on Global Warming

BIOGEOCHEMICAL CYCLES

Ironing out greenhouse effects

Robin S. Keir

IT has been proposed that CO_2 could be removed from the atmosphere and thereby its greenhouse effect reduced by using the so-called 'iron hypothesis' of Martin[1]. According to this idea, iron is the limiting nutrient for biological growth in Antarctic surface waters, which have abundant phosphate, nitrate and silicate. By fertilizing this area with iron, phytoplankton growth would be greatly stimulated, and the surface-water's partial pressure of CO_2 would be greatly reduced — by more than 150 parts per million (p.p.m.). But even if the fertilization were completely successful, the effect on atmospheric CO_2 would be much smaller according to Peng and Broecker on page 227 of this issue[2]. Their model calculations show that after 100 years of successful fertilization, the atmospheric CO_2 content would be reduced only by about 30 p.p.m., an amount which is also small in comparison to the hundreds of parts per million the concentration is projected to rise during this time owing to fossil-fuel burning.

The authors point out that the problem is that the capacity of the Antarctic surface water by itself to take up atmospheric CO_2 is very small. Therefore this region acts only as an interface through which additional CO_2 could be sequestered from the atmosphere and transferred into the large volume of intermediate and deep waters. The rate of this transfer depends upon the nature of the circulation: the speed with which the upper waters are replaced and the extent to which they remain in contact with the atmosphere afterwards.

The model simulations on page 228 (their Fig. 3) illustrate this aspect quite clearly. Initially there is a transitory period of a few years during which the CO_2 partial pressure (p_{CO_2}) in the surface water decreases rapidly and subsequently recovers to within 30 p.p.m. or so of the atmospheric value. The latter evidently occurs because of rapid exchange of CO_2 across the sea surface. After this transient, the surface p_{CO_2} maintains a nearly constant disequilibrium with the atmosphere. The resulting decrease in atmospheric CO_2 is quite slow; the time constant is probably of the order of a few hundred years[3]. The Antarctic surface water is flushed every few years by the circulation, but for every turnover the water takes up only a small part of the atmospheric CO_2 so that the time constant for CO_2 removal is about 100 times the water residence time.

The result found by Peng and Broecker is found to be somewhat model dependent. Indeed, Joos *et al.*[4] using a different circulation pattern through the Antarctic surface region and larger surface area find that the disequilibrium between the atmospheric and Antarctic surface water p_{CO_2} is maintained at a larger value. The consequent reduction in the rate of increase of atmospheric CO_2 is also somewhat greater.

Surely, in looking at how to tackle the threat of greenhouse warming, we should not focus on which model of iron fertilization gives the best result (the possibility of undesirable ecological effects put to one side for the moment), but rather we should worry about the increasing rates of fossil-fuel consumption. The total scale of fossil-fuel reserves is not known with any certainty, but most estimates are between 6 and 12 times the present amount of carbon in the atmosphere as CO_2, mostly as coal[5]. Barring increased uptake by the terrestrial biosphere, which seems unlikely because of deforestation, 70–80 per cent of this carbon will accumulate in the atmosphere if it is burned over a period of a few hundred years, regardless of the actual history of the CO_2 generation over this period[6]. When we have consumed most of the fossil fuel, the atmosphere will have reached a level of at least 1,500 p.p.m. from its present level of around 345 p.p.m.: at this point it may not matter whether a sequestering effort reduced the atmospheric CO_2 by 30 p.p.m. or 300 p.p.m.

However, exactly when the maximum CO_2 level will be reached can vary greatly. For example, a slowly growing production of CO_2 may result in only a doubling of the atmospheric content by the year 2100, but expansion of CO_2 production at the pre-1973 rate of 4.5 per cent a year could lead to levels over 1,200 p.p.m. by then[6]. Because fossil fuel is a finite resource, we will need to find an alternative within the next two or three centuries (sooner if substantial consumption of coal is to be avoided). The slower that fossil fuel is burned in the meantime, the better. Neither iron fertilization nor any other method of CO_2 sequestration can be considered a serious alternative. □

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DAEDALUS

In two minds

EACH hemisphere of the human brain has its own specialism. The left hemisphere (which dominates the right side of the body) is good at language and logic; the right hemisphere (dominating the left side) has better spatial awareness and emotional intuition. Daedalus points out how our view of a knotty problem tends to shift cyclically back and forth every few hours or so. This, he says, is our two hemispheres looking at the matter in turn.

He relates this alternation of mood to our nostrils, which have to warm and humidify the air before it reaches our lungs. It's a hard job. It can drain 5–15 watts of heat continuously from the warming and wetting surfaces, and the nostrils tend to open alternately, a few hours at a time. (You notice this when you have a cold.) Each hemisphere of the brain puts out only about 10 watts of heat. The active n[illegible]ll, draining heat copiously from the hemisphere close above it, must cool it strongly. The brain is very sensitive to temperature, growing feverish in the warm and sleepy in the cold. So as each nostril opens up in turn, the hemisphere on that side grows sleepy, and our mood swings accordingly.

In this connection, Daedalus recalls the traditional yoga exercise of breathing in through one nostril and out the other. The nostril of inflow gets no relief from warm exhaled breath, and must cool its h[illegible]sphere very strongly — a subtle yogic way of opening the mind to new percepti[illegible]. Daedalus's 'psychonasal air-conditioner' provides each nostril with its own air, of defined temperature and humidity. It can fire up or chill out either hemisphere at will. Plumbed into the prototype, DREADCO volunteers are tackling the usual psychiatrists' battery of insulting questions and emotional ordeals. With its aid, the sternest logicians are enjoying flights of fancy, while poets buckle down to mathematical proofs.

The final 'Psyconditioner' will be a special hat with concealed plumbing and heat-pump, and integral nose-piece. By controlling the wearer's nostril-air, it will expand his consciousness under full control. Modern, highly verbal society tends to put the right hemisphere at a disadvantage; the Psyconditioner will allow anyone to get in touch with his intuitive nature. Its wearer will be able to look at a problem first logically, then intuitively — then (with the aid of a special superheater) with fevered imagination, and even with fevered logic. At a picture-gallery or social function he will engage his right hemisphere, while the small print of an insurance-contract will engross his left one. The most inhibited or undisciplined wearer will be able to experience previously suppressed aspects of his personality — and suppress them again as necessary.

David Jones

possible source for the two-level systems would be tipping of the central phenyl ring of *p*-terphenyl between various allowed orientations that are made accessible by disorder in the crystal structure[17]. Validation of this model requires detailed temperature-dependent measurements of the jump rate for a single centre over a wide range of temperature in hope of observing the characteristic coth$(E/2kT)$ dependence, where E is the energy splitting in an asymmetric two-level model and k is Boltzmann's constant.

As the spectral jump rates and sizes that we observe are different for different defects, direct observation of this spectral diffusion effect would not be possible in any spectroscopy that averages over many defects. Direct measurement of the behaviour of individual guest molecules in a glass would lead to a clearer understanding of the origins of dynamics in amorphous solids[18,19] than is available from ensemble-averaged measurements. Much more intriguing is the fact that we have seen spectral jumping in a crystalline environment, where such an effect is not expected. □

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Dynamical limitations on the Antarctic iron fertilization strategy

T.-H. Peng* & W. S. Broecker†

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MARTIN *et al.* have proposed an ingenious means by which the rise in atmospheric CO_2 content generated by the burning of fossil fuels and deforestation might be partially compensated[1]. The idea is that plant production in the nutrient-rich surface waters of the Antarctic could be stimulated by the addition of dissolved iron, thereby reducing the CO_2 partial pressure in these waters and allowing CO_2 to flow from the atmosphere into the Antarctic Ocean. We have used a box model calibrated with transient tracer data to examine the dynamical aspects of this proposal, and conclude that after 100 years of totally successful fertilization the CO_2 content of the atmosphere would be lowered by only $10 \pm 5\%$ below what it would have been in the absence of fertilization. So if after 100 years the CO_2 content of the atmosphere were 500 µatm without fertilization, it would be between 425 and 475 µatm with full fertilization. In other words, if our model calibration is correct, even if iron fertilization worked perfectly it would not significantly reduce the atmospheric CO_2 content.

The CO_2 partial pressure in surface ocean water is influenced by the extent to which plant growth reduces the total CO_2 content, ΣCO_2, of surface water. The magnitude of this reduction depends on the efficiency with which the limiting nutrients phosphate and nitrate are utilized. In today's temperate and tropical ocean the utilization efficiency is high and therefore the reduction of the CO_2 partial pressure, p_{CO_2}, is near maximum. By contrast, the utilization efficiency is low in the polar oceans. Hence, were a means to be found to increase the efficiency of nutrient utilization in these waters, their CO_2 partial pressure and in turn that for the atmosphere, could be reduced. Martin and his co-workers[2-6] have shown in incubation experiments that plant growth rates in waters from polar regions can be greatly accelerated by adding trace amounts of dissolved iron. Iron is an essential micronutrient required for the metabolism of all forms of life, its primary function being cytochrome formation. Because iron is one of the most particle-reactive elements, its concentration in the sea is very low, with the lowest values occurring in regions like the Antarctic that are most removed from the continents.

To date, most of the attention regarding the Martin proposal has been focused on its biological aspects[1] and little attention has been given to the dynamical aspects. Even though successful iron fertilization would initially produce up to a twofold decrease in the CO_2 partial pressure in Antarctic surface waters, this reduction might be short-lived. In the absence of water circulation, only an amount of CO_2 equal to that removed as a result of the initial iron fertilization would be sequestered from the atmosphere. In this case, the atmosphere, the Antarctic surface ocean and the non-Antarctic surface ocean would

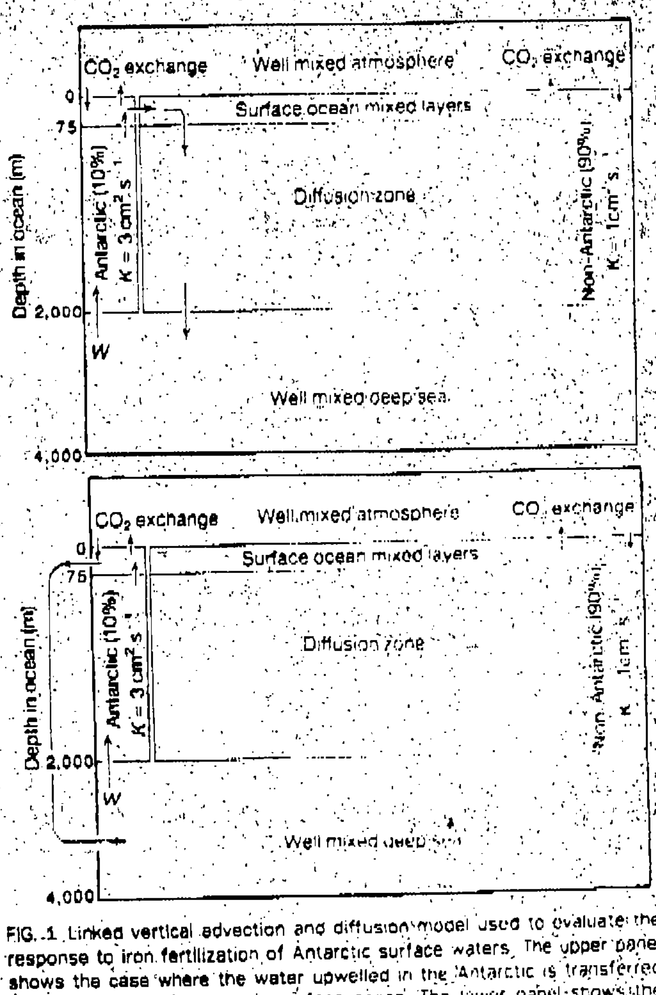


FIG. 1 Linked vertical advection and diffusion model used to evaluate the response to iron fertilization of Antarctic surface waters. The upper panel shows the case where the water upwelled in the Antarctic is transferred laterally to the non-Antarctic surface ocean. The lower panel shows the case where this upwelled water is converted to deep water and transferred directly to the model's deep reservoir.

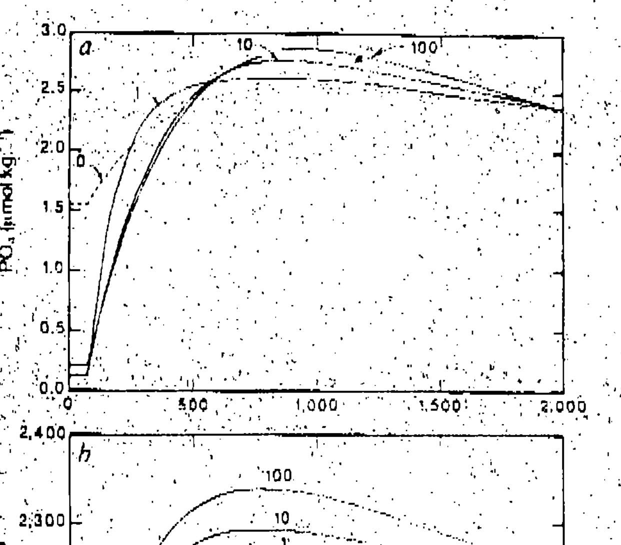


FIG. 2 Vertical distribution of a, PO_4 and b, ΣCO_2 in the Antarctic column before the onset of fertilization (dashed line) and 1, 10 and 100 years after the onset of fertilization for the scenario where water is upwelled at the rate of 17.4 Sv and transferred to the deep sea.

rapidly reach a new equilibrium, leaving the atmosphere with a CO_2 content only slightly lower than it had before fertilization. To achieve a significant reduction of the atmosphere's CO_2 content the surface waters of the Antarctic must be replaced frequently from below.

Thus the critical issue is the rate of vertical mixing in the Antarctic Ocean. Traditional thinking is that deep ocean water upwells in this region. A portion of this upwelled water moves beneath the Antarctic's sea-ice fringe where it is densified by brine release causing it to sink back into the deep sea. The remainder moves to the north. Part is converted to intermediate water which penetrates northward into the Atlantic, Pacific and Indian oceans at a depth of ~1,000 m. The remainder is mixed into the temperate surface water.

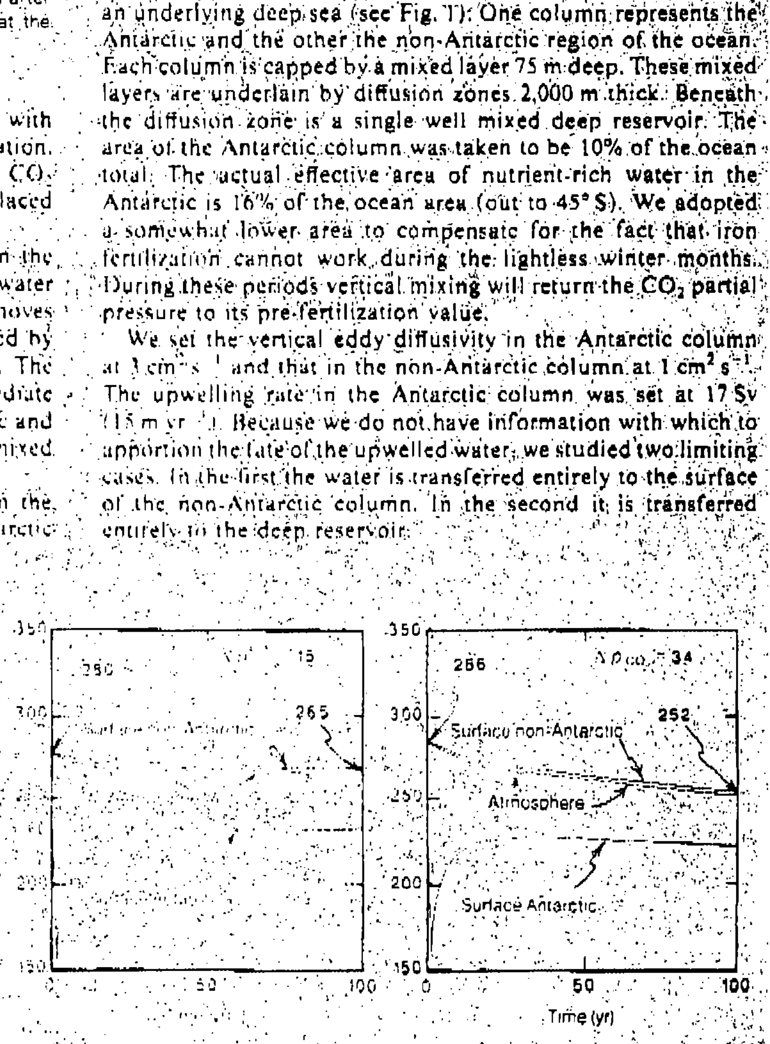
Confirmation of the upwelling hypothesis comes from the inventories of bomb-produced radiocarbon in the Antarctic Ocean as measured during the GEOSECS surveys of the world ocean[8-10]. These results show that the Antarctic waters contain far less bomb-produced radiocarbon than invaded this region from the atmosphere[11]. By contrast, the temperate region of the Southern Hemisphere ocean has an inventory exceeding the amount received by invasion. This excess roughly balances the deficiency in the Antarctic. This pattern can only be explained by upwelling in the Antarctic coupled with lateral transport to the adjacent temperate regions[11]. The upwelling rate required to explain the Antarctic deficiency is 15 m yr^{-1} (ref. 11). As the low bomb-radiocarbon water in the Antarctic Ocean covers ~10% of the total ocean area, this corresponds to a flux of 17 Sv (17×10^6 m^3 s^{-1}).

In addition to upwelling, account must be taken of the extent of vertical mixing. The mean penetration depth of the bomb radiocarbon for the fifteen GEOSECS radiocarbon profiles for latitudes south of 49° S is 260 m (ref. 11). This extent of penetration into the upwelling plume can be explained[11] using a vertical eddy diffusivity of ~3 cm^2 s^{-1} (the steady-state tracer penetration depth into such a plume would be 630 m). Hence, if this interpretation of the bomb-radiocarbon data is correct, the volume of water immediately beneath the Antarctic surface available for CO_2 storage is only 2.2×10^{16} m^3 (630 m $\times 3.5 \times 10^{13}$ m^2) or 1.8% of the ocean's volume, a volume too small to house a significant amount of excess CO_2. Thus it is the fate of the upwelled water that matters. Additional storage capacity will be provided by that portion of the upwelling water that is converted to bottom water along the southern fringe of the Antarctic or to intermediate waters along the northern fringe of the Antarctic.

We devised a simple model to test our ideas. Two box-diffusion columns[12] are linked by an overlying atmosphere and an underlying deep sea (see Fig. 1). One column represents the Antarctic and the other the non-Antarctic region of the ocean. Each column is capped by a mixed layer 75 m deep. These mixed layers are underlain by diffusion zones 2,000 m thick. Beneath the diffusion zone is a single well mixed deep reservoir. The area of the Antarctic column was taken to be 10% of the ocean total. The actual effective area of nutrient-rich water in the Antarctic is 16% of the ocean area (out to 45° S). We adopted a somewhat lower area to compensate for the fact that iron fertilization cannot work during the lightless winter months. During these periods vertical mixing will return the CO_2 partial pressure to its pre-fertilization value.

We set the vertical eddy diffusivity in the Antarctic column at 3 cm^2 s^{-1} and that in the non-Antarctic column at 1 cm^2 s^{-1}. The upwelling rate in the Antarctic column was set at 17 Sv (15 m yr^{-1}). Because we do not have information with which to apportion the fate of the upwelled water, we studied two limiting cases. In the first the water is transferred entirely to the surface of the non-Antarctic column. In the second it is transferred entirely to the deep reservoir.

FIG. 3 Model runs for an Antarctic upwelling flux of 17.4 Sv. Left-hand panel shows the case where the upwelled water is transferred to the surface of the non-Antarctic Ocean and the right-hand panel shows the case where the upwelled water is transferred to the deep sea. In each case totally successful iron fertilization is conducted for 100 years. For the steady-state conditions before fertilization the pCO_2 for Antarctic surface waters is nearly identical to that for the atmosphere.



We started our calculation with the carbon cycle in a steady state. The residence times for PO_4 with respect to biological removal from the surface reservoirs were set to yield 1.6 μmol per kg PO_4 in the surface water above the Antarctic column and no PO_4 in the surface waters of the non-Antarctic column. The regeneration function for falling organic debris was set to yield PO_4 depth profiles similar to those observed (the choice of this regeneration function has no influence on the result of the calculation of the atmospheric CO_2 response to iron fertilization). The atom ratio of carbon to phosphorus in the organic matter falling from the surface mixed layer was 130. We then adjusted the ΣCO_2/alkalinity ratio in the model ocean to yield an atmospheric p_{CO_2} of 280 μatm.

We simulated a totally successful iron fertilization by greatly decreasing the residence time (with respect to biological removal) of PO_4 in Antarctic surface water, bringing its PO_4 content to near zero, and continued the iron fertilization for 100 years. Figure 2 shows the evolution of the vertical distributions of PO_4 and ΣCO_2 in the Antarctic column for the deep-transport case. The total PO_4 in the water column remains unchanged but a bulge of excess ΣCO_2 appears, representing the CO_2 transferred from the atmosphere to the Antarctic water column. In the lateral-transfer scenario (see Fig. 3), the atmospheric CO_2 content drops ever more slowly, reaching an asymptote ~15 μatm lower than the initial value. In the deep-transfer scenario the decrease continues, reaching ~34 μatm after 100 years. The reason for the difference is that in one case the surface water from the Antarctic is transferred to the surface of the non-Antarctic region, allowing the excess CO_2 to re-enter the atmosphere, whereas in the other this water is removed to the deep sea, isolating it from the atmosphere.

As a sensitivity test we have changed the upwelling rate for the deep-transfer case. A rate of 8.7 Sv yields a drop in atmospheric p_{CO_2} of 28 μatm and that of 34.8 Sv a drop of 47 μatm. The question naturally arises as to what would happen if iron fertilization were terminated. Our model shows that any reduction in atmospheric CO_2 content accomplished by the fertilization would be lost, on more or less the same timescale as it was gained.

Clearly, the key to the evaluation of the iron-fertilization scheme is the rate of vertical overturn in the Antarctic. If our interpretation of the bomb-radiocarbon record is correct, then this process is too slow to create a significant decrease in the CO_2 content of the atmosphere. The distribution of freons in the Antarctic water column offers further evidence in this regard. The single published freon section[13], a meridional traverse across the Atlantic sector of the Antarctic, shows that the freon concentration for the entire water column between 500 m below the surface and 500 m above the bottom is <6% of the surface concentration. Although we have not formally modelled freons, this result is broadly consistent with the dynamics adopted here. In any case, such surveys offer constraints on the rates of both deep- and intermediate-water formation. As such information is critical to the evaluation of temperature buffering of the greenhouse warming by the Antarctic Ocean[14], as well as to evaluation of the iron fertilization scheme, its procurement should be placed high on the list of environmental research priorities. □

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ACKNOWLEDGEMENTS. Discussions with J. Sarmiento prompted this study. He also pointed out an important mistake in our paper. We had assumed that the reductions obtained for a steady-state atmosphere with 280 p.p.m. CO_2 applied directly to the anthropogenically perturbed atmosphere. Sarmiento pointed out that this is not correct. We have carried out CO_2-increase models and found that the percentage change in CO_2 partial pressure and not the absolute change that remains approximately the same. We have done the perturbation calculations and find that this is correct. This work was supported by the Lawrence Livermore National Laboratory, Exxon Corporation and the Carbon Dioxide Research Program (W.S.B.) and by the U.S. Department of Energy (T.H.P.) through a joint contract Martin Marietta Energy Systems Inc.

Control of pore-water chemistry at the base of the Florida escarpment by processes within the platform

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PORE waters collected from seep sediments hosting active chemosynthetic communities[1,2] tend to be rich in sulphide, chloride and ammonium and depleted in sulphate relative to the concentrations in sea water. To investigate the source of the energy-rich compounds and the processes causing low sulphate concentrations in seep-sediment pore waters, we have measured the sulphur isotope composition, $\delta^{34}S$, of pore waters from seep sediments at the base of the West Florida escarpment. The isotopic composition of pore-water sulphate remains approximately constant as its concentration is depleted, indicating that processes within the Florida platform, rather than microbial processes at seep sites, control pore-water chemistry in these sediments. The composition of the seep brines, deduced from a linear mixing model, provides information on processes deep within the platform.

Dense biological communities living on highly sulphidized sediments found at the 3,280-m-deep base of the Florida escarpment are supported by chemosynthetic processes[1,3,4] that use reduced substrates seeping from the highly jointed limestone cliff forming the edge of the Florida platform[2,5] (Fig. 1). These seeps occur along at least 10% of the escarpment base[6]. Sedimentary pore waters beneath the large populations of mussels and tube worms are enriched in ammonium (up to 2 mM)[7], radiocarbon-depleted biogenic methane (up to 10 mM)[5,8] and sulphide (up to 5.7 mM). Sediments consisting of >30% sulphide minerals have been reported[9]. The acidity generated by sea-floor oxidation of dissolved sulphide has been suggested as one mechanism for undercutting and eroding the edge of the carbonate continental margin[2].

We collected sediment cores in these chemosynthetic communities with the submersible *Alvin*. The pore waters were expressed from sediments by pressure filtration. Depth profiles of pore-water concentrations show chloride and ammonium enrichment and corresponding sulphate depletion relative to overlying sea water (Fig. 2). Both pore-water sulphate and ammonium are linearly correlated with pore-water chloride concentrations (Fig. 3), indicating conservative mixing between sea water and a sulphate-depleted, ammonium-rich brine. The chloride–sulphate trend yields a value of 27.5‰ for a sulphate concentration of zero, suggesting that this is the chlorinity of the brine exiting the platform at the sea floor. The equation fitting the chloride–ammonium data yields a value of 2.2 mM for the concentration of ammonium in the sulphate-depleted brine.

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tion growth will be in the Third World. What is unexpected is that the data show developing countries are already major sources."

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Reducing Industrial Emissions Can Reverse Effects of Acid Rain on Lakes

According to a report in the 31 May issue of *Nature*, acidified lakes are capable of rapid biological recovery when industrial emissions are reduced. This means that simply cutting back on SO_2 emissions may have direct benefits for acid-endangered lakes; elaborate schemes for liming and otherwise neutralizing lake pH may be unnecessary.

The authors, J.M. Gunn and W. Keller, of the Ontario Ministry of Natural Resources and the Ontario Ministry of Environment, respectively, monitored water quality and biological characteristics of a lake near Sudbury, Ontario (Canada) from 1978 to 1988. Average yearly SO_2 emissions from the Sudbury metal smelters dropped from over one million metric tons in 1975-79 to 718,000 tons in 1988. The average pH during the study period rose from 5.4 in 1980 to 5.9 in 1988.

Lake trout reproduced successfully in the lake after pH rose above 5.5, and invertebrate populations changed dramatically with both the changing balance of fish species and the increased water quality.

The authors note that many other lakes in the Sudbury region showed increased pH after SO_2 emissions declined, and they conclude that "conditions suitable for the survival and reproduction of lake trout and other acid-sensitive organisms can return without liming or other ameliorative treatments."

Algae-CO_2 Connection Draws Ironic Attention

A report in the 10 May issue of *Nature* (vol. 345, pp. 156-157) by John Martin of the Moss Landing Marine Laboratory (Moss Landing, California, USA) indicates that iron could be a major limiting factor for phytoplankton. A lack of iron "prevents [the algae] from blooming and using up the luxuriant supplies of major nutrients found in vast areas of the southern ocean."

This in itself is not terribly controversial. Martin has found that levels of iron are extremely low in southern oceans, and he provides a note at the end of his paper indicating that subsequent experiments in the Ross Sea have indeed stimulated phytoplankton productivity.

But Martin has gone a step further. Since increased phytoplankton activity will take CO_2 out of the air, he reasons, why not add a lot of iron to the oceans to combat climate change? This proposal, reminiscent of biomanipulation projects to reverse lake eutrophication by introducing new fish species, has met with a wide range of reactions, and a lot of attention.

As Christopher Anderson notes in the 31 May issue of *Nature*, "Biologists, noting the deadly effects of algal blooms in the Adriatic, are concerned about the impact on the food chain. Oceanographers and atmospheric scientists say that the phytoplankton may simply release most of the carbon back rather than sinking to the ocean floor. And some policy analysts worry that if every industry could fill a tanker with iron to atone for its carbon sins, few would take expensive and restrictive measures to keep emissions down."

But a number of US agencies have expressed interest in Martin's proposal, and Anderson reports that the National Research Council will hold a conference on this topic (to follow up a conference held last December) later this year.

UK Opens New Climate Research Center

On 25 May, UK Prime Minister Margaret Thatcher opened the Meteorological Office's Hadley Center for Climate Prediction and Research, at Bracknell, UK. According to the Met Office, the immediate research goals of the new center are to: 1) predict global climate change to the year 2100; 2) provide the foundation for improved predictions of regional climate change; and 3) provide a focus for national research programs relevant to the prediction of climate change. The center will be funded at £5.5 million (US $9.2 million) per year.

The center will coordinate Met Office climate research efforts, and will act in concert with other UK research institutions.

For more information, contact the Hadley Center, Meteorological Office, London Road, Bracknell, Berkshire, UK RG12 2SZ. Tel: +44-344-856655; Fax: +44-344-854942.

ness of weatherization and commercial tax incentive and loan programs.

State transportation options include setting (and enforcing) a 55 mile per hour speed limit statewide, converting Oregon private and public vehicle fleets to natural gas, converting all intra-city buses in the state to natural gas by the year 2005, and a number of initiatives to reduce vehicular use in the city of Portland. Electricity options include a moratorium on new coal power plants in the region, and phasing out some existing coal plants after 1997 while adding an additional 900 megawatts of renewable energy sources in the region by 2005. On the sink side, ODOE proposes planting large areas of unstocked or underproductive timberlands. Boosting recycling programs would also help decrease CO_2 emissions.

For other greenhouse gases, ODOE proposes mandatory recycling of CFCs, reducing methane emissions from cattle (through low-methane diets, reducing beef consumption, increasing reproductive efficiency, and reducing methane emissions from animal wastes), capturing methane from landfills, reducing transportation fuel use and natural gas use, and reducing gas emissions from coal mines.

Written comments on the strategy are due by 10 December; for a copy of the energy plan, contact John Savage, Administrator, Policy and Planning Division, Oregon Dept. of Energy, 625 Marion Street NE, Salem, OR 97310. Tel: +1-503-378-4040; Fax: +1-503-373-7806.

Science Update

Northern Lake Ecology Disrupted by Climate Warming

Some of the most severe effects of greenhouse warming are expected in high northern latitudes, where the temperature change is predicted to be greatest and the ecosystems are easily stressed. A new report, appearing in the 16 November issue of *Science* (vol. 250, pp. 967-970), gives an empirical preview of climate change's impact on boreal lakes and their surrounding watersheds.

Over the past 20 years, according to the report, average air and water temperatures in the Experimental Lakes Area of northwestern Ontario, Canada, have risen 2°C. Coincident with this change has been a decline in precipitation and runoff, and a dramatic increase in the time it takes for lakes to replenish lost water — from 4.6 years to over 20 years. The droughts have increased the occurrence of fires in the watershed, resulting in greater wind velocities over the lakes.

The effects of these changes on the lakes are complex. The research team, led by David Schindler of the University of Alberta (Edmonton, Alberta, Canada), found that lower water levels in the lake studied led to an increase in nitrogen (a key nutrient), which along with the temperature rise caused certain phytoplankton populations to grow. The scientists also recorded a slight increase in the phytoplankton species diversity. On the other hand, the longer ice-free season and decreased snowfall, the clearer water (a result of the lowered runoff), and the increased wind velocity, combined to increase the depth of the warm-water layer. This is bad news for cold-loving species such as lake trout, which may die out in the more shallow lakes as the growing warm layer compresses or eliminates the cold, oxygen-rich layer near the bottom.

Regardless of the *cause* of the warming trend recorded by Schindler *et al*, their study represents a landmark analysis of how a real ecosystem responds to a real change in climate.

More on Iron Fertilization: The NRC Workshop

On 29-31 October in Irvine, California, the US National Research Council (NRC) held a workshop on marine algal productivity and carbon dioxide assimilation. NRC released a workshop summary on 16 November.

While some observers have objected to the idea of enhancing CO_2 removal by phytoplankton, a growing number of responsible scientists and policy-makers are seriously considering it as an option to complement anthropogenic emissions reductions. The NRC workshop summary emphasizes that there are still many unanswered questions, and scientists will most likely perform a "Transient Iron Experiment" (TIE) to settle key uncertainties. The TIE would begin sometime in the next 3-5 years, and would involve spreading iron over 400 square kilometers of the Antarctic Ocean. Preliminary assessments indicate that the TIE would have no negative environmental consequences.

As *GECR* reported in the 9 November issue (vol. II, no. 19, pp. 4-5), the maximum impact of a totally successful, intensive iron fertilization program would be significant, but not enormous given the scale of the project. The NRC workshop found that iron fertilization over an area of 40 million square kilometers (18 million square miles) would result in an uptake of 1 gigaton of carbon annually. That's a healthy 1/6 of the total amount of carbon released by burning fossil fuels today (1/8 - 1/9 of total anthropogenic emissions when deforestation is factored in), though as one scientist pointed out, it's only 1/28 of the amount some studies project for fossil carbon emissions in the mid-21st century with unconstrained growth. Fertilization would have to take place annually for at least 100 years to ensure that the carbon isn't just released back into the atmosphere through upwelling, and such a program would require spreading 1-5 million tons of iron each year over the area.

Particularly interesting at the NRC workshop was the discussion of potential ecological side effects. Gustav Paffenhofer of the Skidaway Institute of Oceanography (Savannah, Georgia, USA) noted that krill — a vital food for whales, squid, fish, seals, and penguins — might increase with the rising phytoplankton populations. But he warned that as greater amounts of carbon sink toward the ocean floor, microbial activity in the deeper ocean might increase, diminishing the supply of oxygen. Krill eggs develop at depths of several hundred to a thousand meters, and a lack of oxygen there "could mean certain death ...[and] an eventual crash or greater diminution of the krill population..."

Copies of the NRC Bicoastal Session Summary of the Marine Algal Productivity and Carbon Dioxide Assimilation Workshop are available from Dr. Oskar R. Zaborsky, Director, Board on Biology, National Research Council, 2101 Constitution Avenue NW, Washington, DC 20418-0001, USA. Several articles on iron fertilization will also appear in November issue of *Global Biogeochemical Cycles* (vol. 4, no. 1), published by the American Geophysical Union.

Most Methane Budgets Appear Unrealistic

Over the past 10 years, researchers have published nearly a dozen separate estimates of methane emissions from anthropogenic and natural sources. These estimates range widely in both their figures for total emissions and in their ratios of anthropogenic emissions to total emissions. This presents a dilemma that's quite familiar to scientists and policy analysts working on climate change issues: How does one choose the most reliable estimate?

Fortunately, methane experts M.A.K. Khalil and R.A. Rasmussen of the Oregon Graduate Center (Beaverton, Oregon, USA) have come up with guidelines. Presenting their analysis in a recent issue of *Tellus* (vol. 42B, pp. 229-236), Khalil and Rasmussen find that a realistic budget should portray the anthropogenic fraction of total methane emissions at between 40-70%, and total current emissions at between 420-620 teragrams per year. Only two of the 11 global methane budgets they looked at met these conditions. Which two? One was their own 1983 study (Khalil and Rasmussen, *Journal of Geophysical Research*, vol. 88, pp. 5131-5144), and the other was a 1988 paper by Cicerone and Oremland (*Global Biogeochemical Cycles*, vol. 2, pp. 299-327).

Khalil and Rasmussen base their criteria on observed features of the global methane cycle. Significantly, they note that methane sinks may be declining somewhat (see *GECR*, 8 December 1989, pp. 4-5), which may have led to a somewhat longer atmospheric lifetime for the gas.

Study Yields First Measurement of UV Penetration of Antarctic Sea Ice

Studies published two years ago show that algae living on the underside of sea ice surrounding Antarctica are sensitive to ultraviolet (UV) radiation. These algae are important, since they may account for up to 30% of the primary food production in the region; disruptions in their population could have serious effects on the Antarctic ecosystem.

In the November issue of *Geophysical Research Letters* (vol. 17, no. 12, pp. 2177-2179), H.J. Trodahl and R.G. Buckley of, respectively, New Zealand's Victoria University and the New Zealand Department of Scientific and Industrial Research, report that transmission of UV light through sea ice is naturally the greatest during the austral spring, when the ice is relatively transparent.

Unfortunately, early spring is also the time when ozone depletion is at its most severe. Trodahl and Buckley say that the shallow ozone hole of 1988 enhanced the net UV dose under the ice by a factor of approximately four over pre-1975 levels. The 1987 and 1989 (and presumably the 1990) holes yielded about a ten-fold UV enhancement over the pre-1975 levels.

Ken Ryan, a colleague of Buckley's at the Department of Scientific and Industrial Research, told *GECR* that he'd just returned from a trip to Antarctica where he studied the response of algae to the increased UV doses. Ryan said he recorded depressed algal growth rates in every experiment he performed, but his preliminary results did not show the effects worsening significantly with higher doses.

Global Average Temperatures in 1990 Could Reach Record High

As *GECR*'s 26 October Hotline section noted, the global average temperature trend for 1990 shows that — so far, at least — 1990 could end up being the warmest year since the mid-1800s. Here are a few more details:

On 11 October, Phil Jones of the University of East Anglia (Norwich, UK) told a US Senate panel that the temperature record for the first eight months of 1990 "should easily make it the warmest year yet recorded." The first few months were exceptionally warm, especially March.

And on 22 October, Jim Angell of the US National Oceanic and Atmospheric Administration announced that the global average surface air temperature in the early part of this year was the warmest on record. March, April, and May temperatures

Enlisting Marine Algae To Ease Global Warming

Each year, combustion of fossil fuels, deforestation, and other human and natural activities release eight or nine billion tons of carbon — in the form of carbon dioxide — into the Earth's atmosphere. This carbon dioxide is a key player in current concern about global warming; as a "greenhouse gas," it has the effect of trapping heat and preventing it from radiating back into space.

In addition to reducing carbon emissions, scientists have theorized about ways to recapture some of the carbon that is being released. One of the most innovative ways — boosting the amount of carbon dioxide used by marine algae during photosynthesis — was a topic of a workshop in October sponsored by the Research Council's Board on Biology to answer key ecological and economic questions about the feasibility of this approach. Francisco Ayala of the University of California, Irvine, chaired the meeting.

Often dubbed the "Geritol solution," one technique studied by workshop participants calls for "fertilizing" large areas of the world's oceans with iron, an essential nutrient for marine plants that is apparently in short supply in many oceanic waters.

Life in the Sea

Of primary interest to the 40 scientists and others who gathered at the Academies' Beckman Center in Irvine, Calif., were marine algae. To many, algae are best known as the stringy mats of green scum that form in stagnant pools. But algae — and especially marine algae — are a highly variable, often beautiful group of plants.

Microalgae form the bulk of the oceans' plankton, typically microscopic plants that drift with sea currents or, sometimes, have limited powers of locomotion.

At the other end of the size spectrum are the macroalgae, the familiar "seaweeds." These may be rooted to rocks and are the green, brown and red masses that frequently wash ashore when pulled loose from their anchor. The largest marine alga,

Grant Heilman

***Sargassum* (brown algae)**

California kelp, can reach lengths of nearly 100 feet.

Other macroalgae float unattached in the sea. A good example is Sargasso Weed, which forms dense mats across much of the Sargasso Sea in the tropical Americas.

What all these algae have in common is that they are plants that live by photosynthesis. In the presence of sunlight, water and nutrients, they are able to take up carbon dioxide from the atmosphere and use the carbon to create sugars, starches and other carbohydrates. They release oxygen in the process.

The Iron Hypothesis

The surface of the sea typically has plenty of sunlight and carbon dioxide for algae to utilize in photosynthesis. But some scientists believe that certain nutrients might be lacking in parts of the ocean that limit the ability of algae to reach their maximum productivity.

John Martin of Moss Landing (Calif.) Marine Laboratories has proposed that iron may be a "limiting" nutrient for almost one-fifth of the world's oceans. While iron is one of the most abundant metals in the Earth's crust, it is extremely insoluble in seawater. It is carried to the ocean primarily by wind and suspended in streams and rivers that feed into the sea.

In the open ocean far from land, little iron is available to the algae that grow there.

If iron were introduced into these areas — principally Arctic, Antarctic and equatorial waters — the result should be a marked increase in algal growth and productivity, Martin reasoned.

The Carbon Cycle

Increased algal productivity could have the benefit of significantly reducing the amount of carbon dioxide in the atmosphere, workshop participants concluded. If the algae in iron-poor areas of the ocean reached their peak productivity, they could remove by photosynthesis about 2 billion tons of the 5 billion to 6 billion tons pumped into the atmosphere annually by the combustion of fossil fuels. However, so little is known about the mechanics of the carbon cycle in the ocean and the biology and ecology of the organisms involved that there is no way of accurately predicting the effect or environmental consequences of fertilizing large areas of the ocean with soluble iron, conferees agreed.

Increased algal productivity could have the benefit of significantly reducing the amount of carbon dioxide in the atmosphere.

Workshop participants recommended that a pilot project move forward after about two more years of laboratory research. The pilot project would involve one research vessel periodically spraying soluble iron on a 400-square-kilometer patch of ocean near Antarctica. Workshop attendees said there would be no major environmental consequences for a project of this magnitude.

Ecological Impact

The impact of iron fertilization on the marine environment was one of the critical questions generated by the workshop group. The algae species that currently make up the algal populations in the open ocean are species adapted to iron-poor conditions; these would almost certainly be supplanted by other algae species with unknown repercussions in the food web, said William Sunda of the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration.

Other organisms in the open-ocean community also could be adversely affected, explained Gregory Mitchell of the Marine Research Division of Scripps Institution of Oceanography. Krill, for example, are tiny crustaceans that feed on phytoplankton. They make up the bulk of the diet of many fish and of some whales and therefore are a critical link near the bottom of the food chain. One might expect their populations to burgeon as algae populations grow, he said.

However, the eggs of krill hatch at considerable depths in the ocean. If much organic matter from increased algal populations falls from the ocean surface to these middle levels and decomposes, these waters might become deprived of oxygen. Young krill might die for lack of oxygen. "We just don't know for sure what the impact might be," he said.

Even if environmental problems were somehow surmounted, imposing engineering problems remain.

cost.

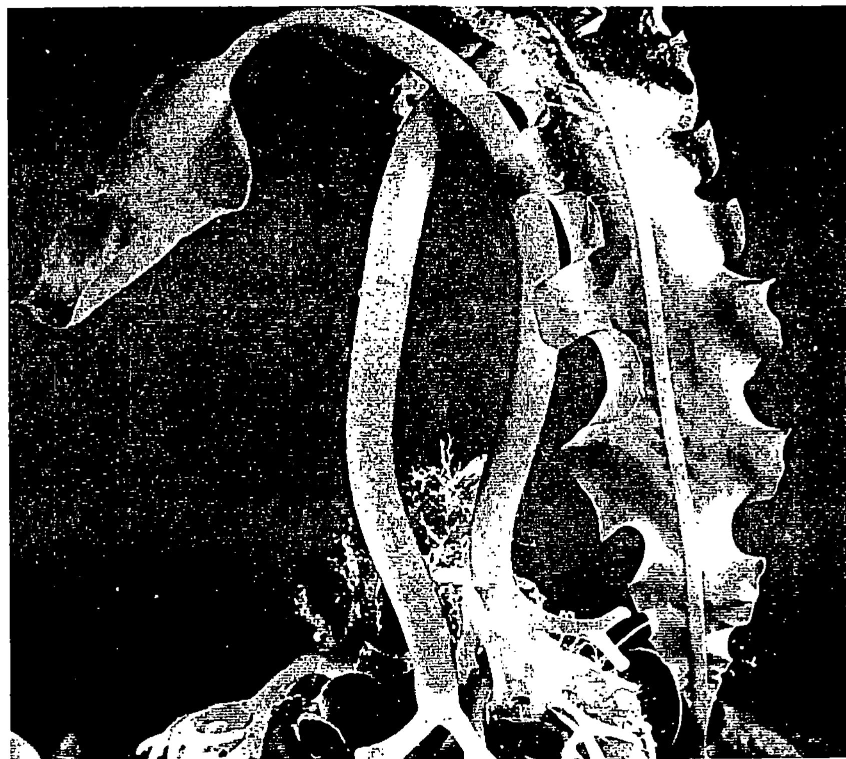
A team of researchers from the E.I. du Pont de Nemours and Co. — Edward Howard and Thomas O'Brien — calculated some of the logistics and cost. For a 600-square-mile area, one would need special barges to haul the ferrous chloride (soluble iron) at a cost of $2.5 billion plus maintenance. They said a flotilla of hundreds of barges and ships would be required to transport and distribute the iron, each operating 365 days a year. Add to this the cost of the iron solution itself and the labor involved, and the proposed bill mounts rapidly.

Macroalgae

Mass farming of macroalgae also was discussed by the meeting participants. Compared to microalgae, however, the contributions of larger seaweeds to increased carbon uptake would be minimal, conferees agreed.

Kelp already has been the subject of considerable experimentation. Wheeler North of the California Institute of Technology has been conducting some of this research.

While microalgae usually are free-floating, most seaweeds are attached to rocks or other substrates. North envisions submerged platforms towed by barges on which the kelp



Grant Heilman

Kelp (brown algae) farms would remove some atmospheric carbon.

are anchored. Fertilizers would be sprayed over the kelp periodically to help them grow, and the kelp plants themselves — composed mostly of carbon in the form of starches and carbohydrates — would be chemically converted into methane and the remaining carbon somehow sunk to the ocean's depths.

However, North noted that experimental designs with which he has worked have not been adequate. Often, the kelp get tangled up in the towing or anchor lines and become no more than a ball of shredded seaweed.

Undaunted by the engineering difficulties posed by both macroalgae and microalgae "farming," conferees agreed that research should proceed.

"We need to resolve questions regardless of the ultimate utility of any ocean fertilization scheme," they wrote in a summary prepared during the meeting. "The area is socially relevant and intellectually engaging."

— *Rick Borchelt*

THE WASHINGTON POST INDEX

SCIENCE NOTEBOOK

Oceanography: Problems With 'Geritol Solution'

Last summer scientists proposed an imaginative but radical solution to the buildup of carbon dioxide in the atmosphere, which many researchers fear could lead to global warming.

Why not, they asked, dump hundreds of thousands of tons of iron fertilizer into the ocean and so create a giant bloom of marine algae? The growing algae would suck carbon dioxide out of the atmosphere and sequester it in the sea. The algae in the Southern Ocean around Antarctica appear to be starving for iron. Scientists half-jokingly called their scheme the "Geritol Solution."

Alas, the Geritol Solution might not work. According to a computer simulation reported in the current issue of the journal Nature, a spurt of algal growth would not be sustained because in the Southern Ocean, the surface waters, where all the action is, are not replaced quickly enough by deeper water that contains other needed nutrients such as phosphorus and nitrogen.

In other words, the algae in the surface water might have all the iron they need, but there may not be enough mixing of the exhausted surface water and nutrient-rich deep water to sustain accelerated growth.

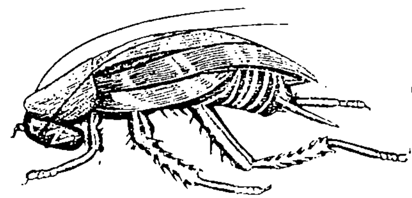
Wallace Broecker of Columbia University and T. H. Peng of Oak Ridge National Laboratory conclude that "even if iron fertilization worked perfectly, it would not significantly reduce atmospheric carbon dioxide content."

—William Booth

Entomology: A New Anti-Cockroach Weapon

In the ongoing war against cockroaches—which has engaged an endless variety of poisons, baits, booby-trapped "motels" and bedroom slippers—scientists have found a new ally: The breeze.

In research conducted by the Agriculture Department's insect research lab in Florida, scientists installed equal numbers of roaches on two sides of an attic. Air vents were installed on one side; the other was left unventilated. In two weeks, most of the insects had fled to the still side. Why?



Experts believe that roaches, which must stay moist to survive, find that a constant breeze dries them out. Researchers suggest that home builders make sure that attics and wall voids are well ventilated.

—Malcolm Gladwel

Pharmacology: Alcohol and Aspirin a Bad Mix

There are few things aspirin can't do. In addition to fighting headaches, arthritis and sundry other

But, according to the scientists, this was because the studies were conducted on people drinking on an empty stomach. In those cases, without

How could it be assessed then wld be no man-made emissions?

...ke place. In all cases no significant anisotropy is observed, indicating that melting is necessary to obtain alignment.

Our method has several advantages over existing techniques. The temperatures and magnetic fields required during sample preparation are relatively modest. The direction of the crystal orientation can be controlled carefully and easily. In addition, because of the relatively rapid cooling rates used during the thermal treatment cycle, the sample production times are significantly shorter than those commonly experienced in melt-texture-growth techniques[7-9]. If the alignment is due to the presence of anisotropic magnetic particles into a liquid, the efficiency of the process will depend on the size and the number of nuclei that are aligned by the field, and consequently on the heating rate, the time and the temperature of the annealing and the cooling rate, all of which govern the grain growth. The process could be adapted for industrial production of textured samples and may prove to be generally applicable to all magnetic substances that have a residual magnetic anisotropy at high temperature. □

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Estimates of the effect of Southern Ocean iron fertilization on atmospheric CO_2 concentrations

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It has been suggested[1-3] that fertilizing the ocean with iron might offset the continuing increase in atmospheric CO_2 by enhancing the biological uptake of carbon, thereby decreasing the surface-ocean partial pressure of CO_2 and drawing down CO_2 from the atmosphere. Using a box model, we present estimates of the maximum possible effect of iron fertilization, assuming that iron is continuously added to the phosphate-rich waters of the Southern Ocean, which corresponds to 16% of the world ocean surface. We find that after 100 years of fertilization, the atmospheric CO_2 concentration would be 59 p.p.m. below what it would have been with no fertilization, assuming no anthropogenic CO_2 emissions, and 90–107 p.p.m. less when anthropogenic emissions are included in the calculation. Such a large uptake of CO_2 is unlikely to be achieved in practice, owing to a variety of constraints that require further study; the effect of iron fertilization on the ecology of the Southern Ocean also remains to be evaluated. Thus, the most effective and reliable strategy for reducing future increases in atmospheric CO_2 continues to be control of anthropogenic emissions.

A flux of dead biogenic organic matter from the ocean surface continuously transports carbon (and nutrients) to depth and thus influences the surface concentration of total dissolved inorganic carbon (ΣCO_2). Model studies have shown that variations in the efficiency of biological uptake and export of organic carbon in the Southern Ocean, where concentrations of the nutrients P and N are high, can lead to alterations of atmospheric CO_2 in excess of 100 p.p.m.[4-7]. Recently, it has been suggested that biological production in these regions may be limited by a restricted supply of iron[8-11]. Although the hypothesis that iron is the ultimate limiting factor there is controversial[12-14], we adopt it here to obtain upper-limit estimates of the possible reduction in atmospheric CO_2. Because the ratio of iron to carbon incorporated in plants is rather low, between 1:10,000 and 1:100,000[15,16], the amount of iron required to carry out this fertilization is relatively modest: $\sim 10^6$ tons of iron per year assuming that all the iron goes into organic matter. Our model study differs from that of Peng and Broecker[17] in the area fertilized (16% of the world ocean rather than 10%), and in that we include scenarios with anthropogenic CO_2 emissions for which we find that fertilization has a greater effect than when we assume no man-made emissions.

We consider there to be three factors that exert the most important control on the response of atmospheric CO_2 to an

HILDA Model

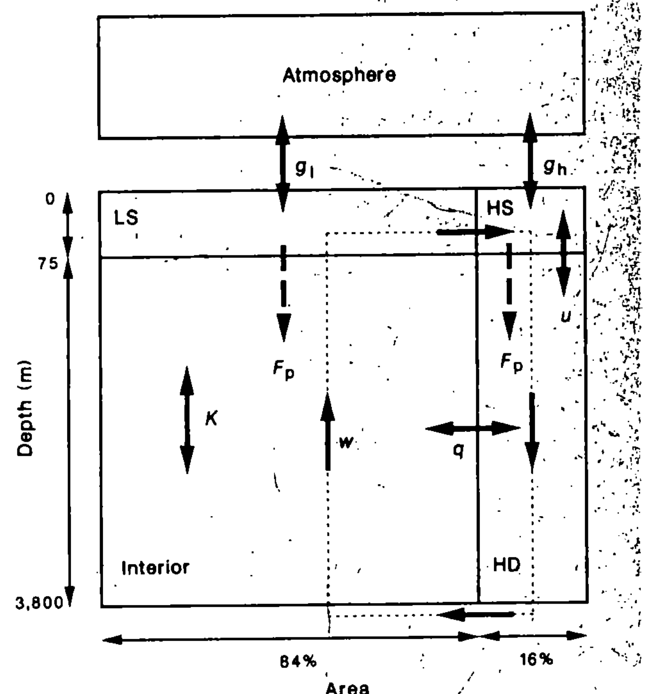

FIG. 1 Structure of the model used for our study, which is based on a model developed by G. Shaffer (personal communication) and one of us (J.L.S.). The ocean interior is resolved by a vertical stack of boxes connected by advection (w) and diffusion (K). The high-latitude regions are simulated by two well-mixed boxes which are connected to each other by mixing (u). The parameter q is a rudimentary representation of the ven[illegible]on of the interior oceans by high-latitude waters. The model parameters obtained by fitting bomb and natural ^{14}C are: $K = 465 + 7{,}096 \times \exp(-(z - 75\ m)/253\ m)\ m^2\ yr^{-1}$; $w = 0.44\ m\ yr^{-1}$ (equivalent to $4.24 \times 10^6\ m^3\ s^{-1}$); $u = 38\ m\ yr^{-1}$ ($69.8 \times 10^6\ m^3\ s^{-1}$); $q = 0.00186\ yr^{-1}$ ($79.5 \times 10^6\ m^3\ s^{-1}$); gas-exchange rate ($g_l$, g_h) at 280 p.p.m. $= 15.1\ mol\ m^{-2}\ yr^{-1}$; ocean surface area $= 3.62 \times 10^{14}\ m^2$; depth of [illegible] layer $= 75$ m; average depth of ocean $= 3{,}800$ m. We solve co[illegible]vation equations for the perturbation of phosphate and CO_2 ($c_{pert.} = c_{actual} - c_{unpert.}$) with an initial condition for $c_{pert.}$ of 0 everywhere. The relation between changes of ΣCO_2 and P_{CO_2} is calculated using the equations of Peng *et al.*[24]. The phosphate and carbon removed from the surface high-latitude box are regenerated to the dissolved form in the deep box below (dashed arrows, F_p = perturbation flux of particulate carbon and phosphorus). A small amount of this excess phosphate makes its way through the [illegible] to low-latitude surface waters, where it is removed and regenerated below with an exponential scale depth of 1,160 m obtained from a fit to oceanic nutrient data by G. Shaffer and J.L.S. Multiplying the resulting phosphate fluxes by the C:P Redfield ratio (130) gives the corresponding carbon fl[illegible] LS, low-latitude surface; HS, high-latitude surface; and HD, high-latitude deep boxes.

TABLE 1 Projected changes in atmospheric CO_2 partial pressures resulting from various scenarios beginning in 1990

Scenario*	After 50 years A Unfertilized	B Fertilized	Effect of fertilization (B−A)	After 100 years C Unfertilized	D Fertilized	Effect of fertilization (D−C)
		High-latitude area fraction=9.7%†				
Initialized at pre-industrial levels						
Our model	0	−26	−26	0	−39	−39
Peng and Broecker‡	—	—	—	0	−34	−34
Constant-emission	80	46	−34	156	98	−58
Business-as-usual	150	114	−36	430	362	−68
		High-latitude area fraction=16.0%				
Initialized at pre-industrial levels	0	−41	−41	0	−59	−59
Constant-emission	79	24	−55	151	61	−90
Business-as-usual	146	88	−58	417	310	−107

* The scenario which is initialized at pre-industrial levels of atmospheric CO_2 has no anthropogenic source of CO_2 to the atmosphere, thus the CO_2 drawdown by the ocean results in a reduction below the initial pre-industrial value of 278.3 p.p.m. In the 'constant-emission' scenario, atmospheric CO_2 content is prescribed using observations until 1990[23], after which the CO_2 emission to the atmosphere is fixed at the model-determined value of 6.15 Gt C yr^{-1} in 1990. In the 'business-as-usual' scenario, the atmospheric CO_2 content is prescribed until 1989, after which the annual emission increases according to the IPCC business-as-usual scenario[22], in which the man-made emissions increase linearly with time from 6.0 Gt C yr^{-1} in 1990 to 22.4 Gt C yr^{-1} in 2100. The 1990 atmospheric CO_2 partial pressure is 355 p.p.m.

† The area fraction of 9.7% in our model corresponds to the same area in m^2 as chosen by Peng and Broecker[17].

‡ The Peng and Broecker[17] model is initialized at 280 p.p.m. and has a phosphate reduction of 1.6 mmol m^{-3}. The result given here is for their scenario with $17.5\times10^6\ m^{-3}\ s^{-2}$ of water upwelling in the high latitudes and being placed directly into the deep ocean.

enhanced carbon uptake resulting from iron fertilization. First is the reduction in average ΣCO_2 per unit area that occurs when fertilization is started. We take the supply of phosphate from depth as a reasonable guide to the maximum potential biological uptake of carbon, although we recognize that light supply, our ability to spread iron efficiently over the large ocean areas involved, the behaviour of the ocean ecosystem, and other processes may interfere long before the phosphate is depleted. (Carbon cycling is linked to that of phosphate through the Redfield ratio of C:P=130 in organic matter.[18]) Second is the area over which the fertilization occurs. We use a recent analysis of National Oceanic Data Center phosphate data (S. Levitus and R. G. Najjar, personal communication) to estimate that the Southern Ocean's (>30° S) water volume in the depth range 0-75 m with phosphate ≥1.0 mmol m^{-3} amounts to 15.8% of the world ocean volume in the same depth range. The average phosphate content of this volume is 1.63 mmol m^{-3}. We therefore take the high-latitude box of our 'standard' model to consist of 16% of the world ocean area (with 9.7% as an alternative case corresponding to the area used by Peng and Broecker[17]), and we determine the enhancement to the biological production by forcing a reduction of phosphate by 1.5 mmol m^{-3} in the surface box of this area. Third is the reduction in CO_2 partial pressure resulting from a given carbon removal. We have found that this is considerably larger at high rather than at low CO_2 levels because of the nonlinear relation between P_{CO_2} and ΣCO_2. We use three different anthropogenic CO_2 emission scenarios to examine the contribution of this nonlinearity, one in which the ocean and atmosphere are initialized at the pre-industrial value of 278 p.p.m. with no anthropogenic sources, a 'constant-emission' scenario, and a 'business-as-usual' scenario (see Table 1 legend for descriptions of the scenarios).

The rate at which atmospheric CO_2 is taken up by the oceans also depends on the rate at which the ocean circulation and mixing transport to the abyss the excess CO_2 that invades the fertilized region from the atmosphere. As discussed below, we find that this factor is less critical than those mentioned above. Figure 1 shows the model we use to simulate the ocean circulation and mixing. Parameter values are obtained by fitting the model to pre-bomb ^{14}C observations as well as the GEOSECS bomb inventory estimates of Broecker *et al.*[19] (U.S. and F.J., to be published elsewhere). However, the bomb inventory estimates in the Southern Ocean were not considered adequate for use in the fitting exercise because the bomb signal is not easy to discern from the natural ^{14}C background; the data in the Southern Ocean are scanty, especially from pre-bomb time; and the bomb inventories south of 46° S show considerable variation. Instead, we checked our model with high-latitude CFC-11 observations, obtaining a standing crop of 1,976 nmol m^{-2} for 1984, comparable to an estimate of 1,950±550 nmol m^{-2} obtained for the same period from measurements south of 46° S by Weiss *et al.*[20] in the South Atlantic, by the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration in the South Pacific (R. H. Gammon and D. Weisgarver, personal communication), and by R. Weiss (personal communication), also in the South Pacific.

Figure 2 summarizes results from the iron fertilization assuming the business-as-usual and constant-emission CO_2 scenarios. Without fertilization, the increase in atmospheric CO_2 from its 1990 value of 355 p.p.m. is 146 p.p.m. after 50 years, and 417 p.p.m. after 100 years in the business-as-usual scenario (Fig. 2*a*). When iron fertilization is initiated, an additional flux of organic carbon out of the high-latitude surface box is stimulated. Its size is approximately constant at 5.5 Gt C yr^{-1} after an initial peak in the first year. This increased carbon flux leads to a massive decrease in the high-latitude surface P_{CO_2} (see Fig. 2*b*), and a resulting enhancement of atmospheric CO_2 uptake so that the atmospheric CO_2 now increases by only 88 p.p.m. after 50 years (60% of the increase in the unfertilized scenario) and by 310 p.p.m. after 100 years (74% of the increase in the unfertilized scenario). The decrease in atmospheric P_{CO_2} resulting from iron fertilization reduces the low-latitude air-sea difference so that the response of the low latitude regions is opposite in sign to that of the high latitudes (Fig. 2*b*). After 100 years, the additional CO_2 flux from the atmosphere to the high-latitude box in the iron fertilization scenario is 2.65 Gt C yr^{-1}. This is partly balanced by a reduction of 0.51 Gt C yr^{-1} in the low-latitude uptake of anthropogenic CO_2, for a net annual oceanic uptake of 2.13 Gt C yr^{-1} due to iron fertilization.

The effect of the nonlinearity of the carbon chemistry equations can be discerned by comparing the three scenarios shown in Table 1. The constant-emission scenario with fertilization of 16% of the world ocean shows a reduction of 90 p.p.m. in the increase of atmospheric CO_2 resulting from 100 years of iron fertilization, compared with 59 p.p.m. for the scenario initialized at 278 p.p.m. The further increase in atmospheric CO_2 in the business-as-usual scenario has a still larger effect: 107 p.p.m. The dependence on the prevailing atmospheric CO_2

concentrations can be understood when considering that P_{CO_2} depends in a nonlinear way on $\Sigma\, CO_2$. The higher the atmospheric concentration of CO_2, the larger the change in oceanic P_{CO_2} for a given reduction of $\Sigma\, CO_2$ due to iron fertilization (see Fig. 2*c*). We find that the percentage reduction in atmospheric CO_2 concentration which would occur after 100 years of iron fertilization decreases with higher CO_2 levels (21% for pre-industrial initialization, 14% for the business-as-usual scenario). This is in contrast to the assertion of Peng and Broecker[17] that the relative reduction is constant.

Peng and Broecker[17] emphasize that the key to evaluating the impact of iron fertilization is the rate of vertical exchange in the Southern Ocean. We find that the uncertainty in the calibration of the high-latitude transport parameters *u* and *w* gives error limits of $^{+14\%}_{-24\%}$ for the absolute value of the iron-induced reduction in atmospheric CO_2 for the pre-industrial scenario. Therefore, the precise magnitude of the vertical exchange seems not to be as critical as uncertainties in other processes. This is also supported by the fact that Peng and Broecker's result agrees well with ours for the same pre-industrial scenario (Table 1), although their high-latitude vertical exchange, which is calibrated with bomb-produced radiocarbon, is considerably weaker than our vertical exchange calibrated by oceanic distribution of CFC-11.

The effect of ocean area is readily apparent from the results summarized in Table 1. An increase in the fertilized area from 9.7% to 16% leads to an almost linear increase in the effect of iron fertilization of ~60%. Broecker[21] argues that their choice of the smaller area was intended to compensate for the fact that much of the Antarctic is in darkness during part of the year. We attempted to compensate for this effect by fertilizing the ocean for only six months of the year. The CO_2 uptake in the business-as-usual case went down from 107 p.p.m. to 88 p.p.m., far less than the drop to 68 p.p.m. which occurs when using the smaller area.

To be effective, iron fertilization has to be applied continuously so that the atmosphere-ocean system does not revert to its unfertilized state. This is shown in Fig. 3, which shows what happens if iron fertilization is terminated after 50 years. At 50 years the ocean in the business-as-usual-iron fertilization simulation has taken up 57.9 p.p.m. more CO_2 than the non-fertilized ocean. If fertilization is stopped at this point, the difference between the fertilized and non-fertilized scenarios reduces to 35.5 p.p.m. after 100 years.

Changes in the Earth's equilibrium temperature are logarithmically related to the atmospheric CO_2 content, with a doubling of CO_2 leading to an equilibrium warming of between 1.5 °C and 4.5 °C, with a preferred value of 2.5 °C (ref. 22). A useful index of the significance of a given CO_2 increase is the factor $\ln(P_{CO_2}/278)/\ln(2)$ which, multiplied by 2.5 °C, will give the equilibrium warming resulting from a given CO_2 increase. Thus, the atmospheric CO_2 concentration of 771 p.p.m. reached by 2090 in the business-as-usual scenario will give an equilibrium warming of 3.7 °C. The 107-p.p.m. additional oceanic uptake

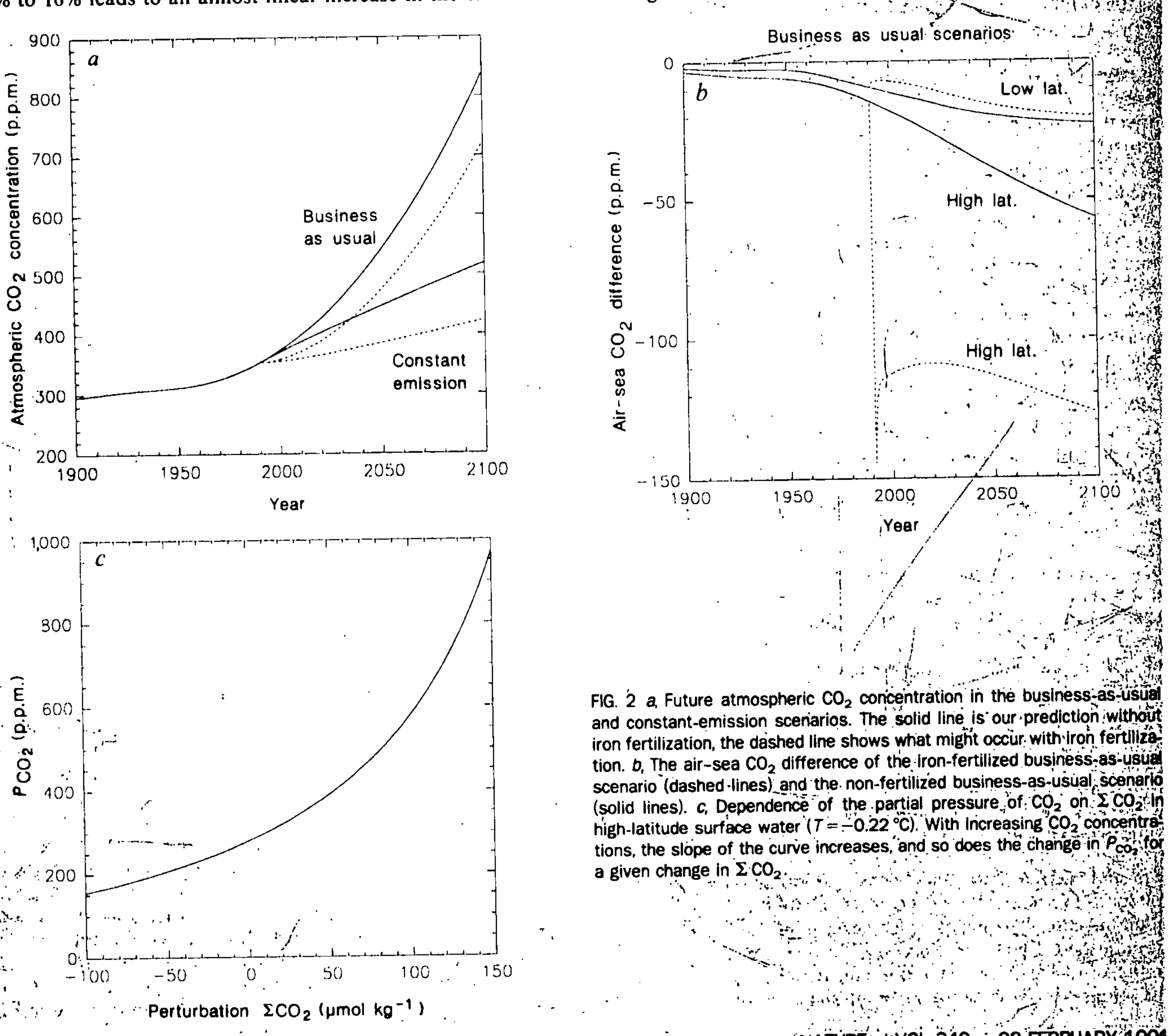

FIG. 2 *a*, Future atmospheric CO_2 concentration in the business-as-usual and constant-emission scenarios. The solid line is our prediction without iron fertilization, the dashed line shows what might occur with iron fertilization. *b*, The air–sea CO_2 difference of the iron-fertilized business-as-usual scenario (dashed lines) and the non-fertilized business-as-usual scenario (solid lines). *c*, Dependence of the partial pressure of CO_2 on $\Sigma\, CO_2$ in high-latitude surface water ($T = -0.22$ °C). With increasing CO_2 concentrations, the slope of the curve increases, and so does the change in P_{CO_2} for a given change in $\Sigma\, CO_2$.

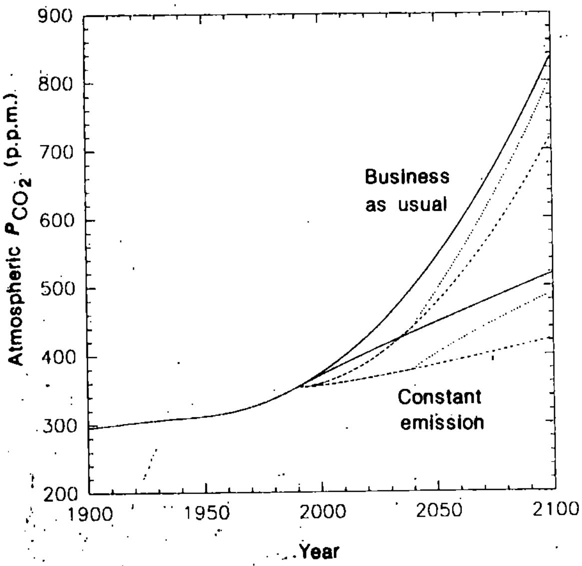

FIG. 3 The effect of stopping iron fertilization after 50 years (dotted line) is depicted for the business-as-usual and constant-emission scenarios. The solid line is the unfertilized scenario; the dashed line is the scenario for continuous fertilization.

resulting from iron fertilization gives an equilibrium warming of 3.1 °C instead. On the other hand, the unfertilized constant-emission scenario, which reaches 505 p.p.m. in 2090, gives a significantly smaller equilibrium warming of 2.2 °C, which is reduced to 1.4 °C with the 90 p.p.m. additional oceanic uptake resulting from iron fertilization. These numbers can be compared with the 0.9 °C equilibrium warming that can be expected from the present atmospheric CO_2 content of 355 p.p.m. It should be kept in mind that the transient warming is smaller than, and not necessarily proportional to the equilibrium warming, due primarily to the uptake of heat by the ocean.

The most important conclusion we draw from our calculations is that, although the effect of iron fertilization is large enough to justify further study, the effect of a significant change in the emissions of CO_2 is even larger. We emphasize the preliminary nature of our calculations and the fact that all the assumptions we have made have been biased so as to yield an upper limit. □

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Biases from natural sulphurization in palaeoenvironmental reconstruction based on hydrocarbon biomarker distributions

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BIOMARKERS (chemical fossils) are sedimentary organic compounds whose basic skeletons suggest an unambiguous link with known contemporary natural products, and were synthesized by biota present at the time of the deposition of the sediment. These compounds are commonly used to assess palaeoenvironmental conditions of deposition of Recent and ancient sediments[1-3]. Saturated hydrocarbons are relatively easy to analyse and contain a lot of geochemical information, and are therefore the most widely used class of biomarkers in palaeoenvironmental reconstruction[2-5]. Hydrocarbon biomarkers are biosynthesized as such or are derived from functionalized biosynthetic lipids, such as alkenes, alcohols and acids, by diagenetically induced defunctionalization. Functionalized lipids may, however, also undergo an abiogenic reaction with hydrogen sulphide or polysulphides ('natural sulphurization') during the early stages of diagenesis, and this may lead to selective removal of specific hydrocarbon biomarker precursors. Here we investigate the influence of natural sulphurization on hydrocarbon biomarker signatures in immature sediments from Italy and off Peru. We show that, if not taken properly into account, this process may lead to a severe bias in the interpretation of the geological record.

Sedimentary functionalized lipids react with reduced sulphur species (H_2S and HS_x^-) to form organic sulphur compounds (OSCs) and sulphur-bound lipid moieties in macromolecules (see ref. 6 for a review). The onset of sulphurization of organic matter is controlled by the reactive iron (for example, ferrihydrite and haematite) content of the sediment; because organic matter reacts with reduced sulphur more slowly than do sedimented iron minerals and thus does so only after reactive iron oxides have first been converted to iron sulphides. In the region of upwelling in the Peru margin, sulphur incorporation into sedimentary organic matter starts in the top metre of the sediment column[7], indicating that this process occurs in the early stages of diagenesis. Moreover, the identification of OSCs in a Recent Black Sea sediment (age $3-6\times10^3$ yr) also points to an early diagenetic sulphurization of organic matter[8]. Ten Haven *et al.*[9] examined the extracts of almost 100 thermally immature deep-sea sediments and found that approximately 70% of the samples contain OSCs. The widespread occurrence of OSCs, and the fact that reduced inorganic sulphur species are present in any anoxic organic-matter-containing Recent marine sediment[10], suggest that natural sulphurization of specific functionalized lipids is a ubiquitous process. It seems inevitable that this selective removal of the precursors of hydrocarbon biomarkers will alter the hydrocarbon biomarker distribution in immature sediments, and thus the interpretation of the geological record as revealed by their apparent distribution. Hydrocarbon biomarkers are used in many (palaeo)environmental reconstruction studies of immature sediments[11-16] and of partion of net CO_2 emissions by 1-2% per year starting now would be required." This still amounts to at least a 20-50% cut in CO_2 over the next 20-50 years, but the stepwise, year-to-year approach makes the target seem less painful and uses a time frame politicians can understand.

More Precise Temperature Estimates Unlikely, Say Researchers

In what US climatologist Stephen Schneider described as "the only original piece of climate science" that he saw presented at the Second World Climate Conference, UK researchers Tom Wigley and Sarah Raper explained that better estimates of the climate's equilibrium response to an equivalent doubling of CO_2 are unlikely to emerge in the next few decades.

If the current observed warming of 0.5°C resulted entirely from an enhanced greenhouse effect, the researchers say, then a doubling of CO_2 should result in a warming of only 1.25 - 1.55°C. Adding the very real factors of natural climate variability and data uncertainties widens the range to 0.65 - 4.05°C. This range becomes even broader when the effects of ocean circulation changes, solar variation, and sulfate aerosols are included. Sulfates, according to Wigley and Raper, may have offset the greenhouse contribution to warming by as much as one third, which means that SO_2 reductions currently underway in many Northern Hemisphere countries could result in a considerably larger warming than might otherwise be expected.

Wigley and Raper point out that no matter what global-mean temperatures do over the next few decades, they won't reduce the range of uncertainty in estimates of the climate's response to a CO_2 doubling. And, significantly, they claim that at least a 2.5°C warming can be expected even if the temperatures remain unchanged for the next 15 years.

Methane Emissions from Lakes Increase as Air Pressure Drops

According to a report in the 25 October issue of *Nature* (vol. 347, pp. 718-719), the bubbles of methane that routinely escape from lakes may become larger and more frequent during periods of low air pressure.

According to the study's authors, Mark Mattson and Gene Likens of the Institute of Ecosystem Studies, Millbrook, New York, USA, more than half the methane fluxes from a New Hampshire lake during a 64-day sampling period in 1989 occurred during a heavy rainfall on 5 August, and a tropical storm on 23 September.

Mattson and Likens also cite earlier research that reported gas releases from soils during low-pressure events; if climate change eventually increases rainfall in certain areas, and increases the frequency of tropical storms, then this methane response represents a potentially significant positive warming feedback.

Molecular Hydrogen Increase May Pose Threat to Ozone Layer

The atmospheric concentration of molecular hydrogen (H_2) has increased to a little over 500 parts per billion since its estimated pre-industrial level of around 200 ppb. And according to a report in the 25 October issue of *Nature* (vol. 347, pp. 743-745), H_2's concentration has increased by about .5% per year between 1985 and 1989. Because H_2 oxidizes to form water vapor, and because an increase in water vapor in the stratosphere may lead to an increase in polar stratospheric clouds, the H_2 trend could be bad news for the ozone layer.

Why is molecular hydrogen increasing? According to the study's authors, M.A.K. Khalil and R.A. Rasmussen of the Oregon Graduate Institute (Beaverton, Oregon, USA), the 1% per year increase in methane emissions "may account for half of the observed trend of H_2," and biomass burning, oxidation of non-methane hydrocarbons, and various anthropogenic activities could account for much of the rest.

The 27 October issue of *Science News* quotes F. Sherwood Rowland of the University of California, Irvine, as saying that methane oxidation should add "significantly more water vapor to the stratosphere than would increasing levels of hydrogen, posing an even greater threat to the ozone layer." Rowland, famous for his early work on CFCs and the ozone layer, has begun to focus much of his attention on greenhouse gas emissions.

Iron Fertilization to Remove CO_2: What's the Potential?

As *GECR* reported on 8 June (p. 6), US scientist John Martin and colleagues have proposed a way to reduce atmospheric CO_2 concentrations by enhancing plant productivity in Antarctic waters. Although the southern ocean is rich in nutrients, algae there are limited by a lack of iron; adding iron to the ocean would stimulate algal growth and take more CO_2 out of the atmosphere.

But how much more? A new estimate, by T.H. Peng and Wallace Broecker of Oak Ridge National Laboratory (Oak Ridge, Tennessee, USA) and the Lamont-Doherty Geological Observatory (Palisades, New York, USA), respectively, concludes that "after 100 years of totally successful fertilization, the atmosphere's CO_2 content would be lowered by 30 parts per million [give or take 10 ppm]." In other words, according to Peng and Broecker, if CO_2 were to reach 500 ppm in the year 2090 under business as usual, a strict program of fertilization over the entire century would lower the concentration to 455-485 ppm. Peng told *GECR* that the relationship isn't linear — most of the effect occurs in the early stages of fertilization, and over a shorter time horizon (50 years), the atmospheric CO_2 concentration would still be lowered by 20-25 ppm. However, Peng cautioned that the estimate is very optimistic, and assumes the process of fertilization and CO_2 removal works "100% perfectly." More realistically, CO_2 concentrations might be lowered by only 15 ppm over the next 50-100 years through an intensive fertilization program.

The two scientists will present the results of their study at the Fall 1990 meeting of the American Geophysical Union, to be held in San Francisco from 3-7 December.

Study Finds High Levels of Methane in Eastern European Cities; Leaks Blamed

F. Sherwood Rowland and colleagues from the University of California at Irvine report in the 4 October issue of *Nature* (vol. 347, pp. 432-433) that recent methane levels in Berlin, Budapest, Krakow, and Prague were "substantially higher ... than those characteristic of most US cities." Rowland, who along with Mario Molina first brought the ozone-depleting potential of CFCs to light, says that leakage during natural gas transmission is probably the culprit.

Rowland says a 10% reduction in global methane emissions should be enough to stabilize its global concentration, "and eliminate any further incremental contribution of this gas to the atmospheric trapping of infrared radiation."

The IPCC's scientific report quotes a figure of 15-20%; Rowland bases his calculation on the fact that methane has increased an average of 1% per year during the 1980s, and that its atmospheric lifetime is about 10 years.

According to Rowland, "improved controls on the tranmission of natural gas, particularly in eastern Europe and Asia, offer a promising opportunity to slow the global build-up of methane..." See ***GECR***'s 22 June issue, p. 6) for a related article.

Industry Watch

US to Facilitate Coordination of Industry's Global Change Research Efforts

The Committee on Earth and Environmental Sciences (CEES, formerly CES), the government body that established and oversees the US Global Change Research Program, is trying to organize a similar program for US industry research on global change.

CEES has set up an informal working group, the Private Industry-Government Interface (PIGI), to act as a communication point between government and industry; the next step, says Dr. Frederick Henderson of the Geosat Committee in Norman, Oklahoma, is to help industry organize a research steering committee that parallels CEES. Henderson acknowledges that coordinating industrial research efforts may be quite difficult, particularly if PIGI aims to be comprehensive. According to Geraldine Cox, vice president of the Chemical Manufacturers Association and chair of the Global Climate Coalition's research committee, the fact that each industry is concerned with its own specific issues will make it hard to duplicate the broad programmatic scale that CEES has established for the Global Change Research Program. ***GECR*** should note that PIGI's program would focus mainly on basic research, not on efforts to mitigate global change.

Henderson and colleagues are organizing a workshop to be held 11-13 February 1991 on industry's "current and planned research that's relevant to the Global Change Research Program." Interested parties should contact Henderson at The Geosat Committee Inc., 601 Elm Street, Room 438C, Norman, OK 73019, USA. Tel: +1-405-325-3329; Fax: +1-405-325-3327.

European Wind Energy Pushes for Major Increases in Capacity

Seeing an opportunity for growth in the face of the European Communities' commitment to reduce CO_2 emissions, the European Wind Energy Association (EWEA) has prepared a strategy that calls for 100,000 megawatts (MW) of wind generating capacity to be installed in the EC by the year 2030. EWEA produced the strategy on contract with the European Commission, and its recommendations are based on an appraisal of technological developments, realistic costs, a comparison with conventional power generation, and reviews of markets, budgets, and subsidies.

According to EWEA President David Lindley, wind energy currently provides about 365 MW in Europe, with 250 MW of that being produced in Denmark. Denmark's Energy 2000 plan requires wind power to increase to 10% of the country's total energy production by the year 2000, up from 2% today. The Netherlands has set a goal of 1,000 MW of wind energy capacity by the year 2000, and is currently soliciting bids for 250 MW worth of new turbines. Germany plans to add 250 MW of wind energy by the year 2000, and is offering major subsidies (US $0.9 per kw/h to wind farmers); Italy wants

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Control of a Desert-Grassland Transition by a Keystone Rodent Guild

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Twelve years after three species of kangaroo rats (*Dipodomys* spp.) were removed from plots of Chihuahuan Desert shrub habitat, density of tall perennial and annual grasses had increased approximately threefold and rodent species typical of arid grassland had colonized. These were just the most recent and dramatic in a series of changes in plants and animals caused by experimental exclusion of *Dipodomys*. In this ecosystem kangaroo rats are a keystone guild: through seed predation and soil disturbance they have major effects on biological diversity and biogeochemical processes.

THE BIOLOGICAL DIVERSITY AND biogeochemical processes that characterize an ecosystem depend on interactions of the organisms with each other and with their abiotic environment. The presence or absence of certain kinds of organisms, called "keystone species" (*1*), can dramatically alter the structure and dynamics of ecological systems. In most ecosystems, vertebrate animals account for only a small fraction of the biomass and energy flow (*2*), but through predator-prey, competitive, and mutualistic interactions with other species and by causing physical disturbance they can have disproportionately large effects on habitat structure, species composition, and biogeochemical processes (*2, 3*). We show that long-term experimental removal of a guild of three kangaroo rat species from a desert ecosystem initiated changes that have led to the conversion of the habitat from shrubland to grassland.

In 1977, experiments were begun on an alluvial outwash plain with diverse desert shrub vegetation in the Chihuahuan Desert of southeastern Arizona (*4, 5*). Twenty-four plots, each 0.25 ha in area (50 by 50 m), were fenced with fine wire mesh and assigned at random to experimental manipulations. Treatments included removal of some or all rodent or ant species and addition of millet seeds (Table 1). Access of different rodent species to appropriate plots was controlled by cutting holes of different sizes at ground level in the fences surrounding the plots. Populations of rodents, ants, birds, and plants were monitored systematically at a grid of permanent sample sites within each plot. Between 4 and 16 September 1989, in order to better characterize plant cover inside and immediately outside each plot, all plant species were counted at 10-cm intervals along eight 25-m transect lines: four inside transects began 8 m from the center of the plot and ran outward toward each corner; after a gap of 2 m on either side of the fence, the other four transects continued for another 25 m outside the fence.

In ten plots, one of three different combinations of desert rodent species was excluded (Table 1): all rodents; three species of kangaroo rats, *Dipodomys spectabilis*, *D. ordii*, and *D. merriami*; or just the largest an[d] behaviorally dominant kangaroo rat, *D[.] spectabilis*. An initial analysis of varianc[e] (ANOVA), with plots as the sample units t[o] avoid "pseudoreplication" (*6*), showed tha[t] treatments in which all rodents or all kangaroo rats had been removed were similar t[o] each other in the plant variables analyze[d] below. They differed significantly from a[ll] other treatments, except *D. spectabilis* removal. In addition, there were no detectabl[e] effects of ant removal or seed addition treatments on these plant variables. Therefore the eight plots where all kangaroo rats wer[e] absent were compared to the 14 plots wher[e] all kangaroo rats were present in the following analyses. The two plots from which jus[t] *D. spectabilis* had been removed were excluded from the analyses, because the vegetatio[n] parameters were often intermediate betwee[n] the two treatment classes and the limite[d] replication did not permit statistical resolution.

Table 1. Schematic representation of t[he] experimental treatments (*4*). All plots wi[th] kangaroo rats removed (−) were compared [to] all other plots (+), except those with *[D.] spectabilis* removed.

Treatment	Numb[er] of plots
Unmanipulated control	2 (+
All rodents removed	2 (−
All rodents and all ants removed	2 (−
Kangaroo rats removed	2 (−
Kangaroo rats and *Pogonomyrmex* ants removed	2 (−
Dipodomys spectabilis removed	2
All ants removed	2 (+
Pogonomyrmex ants removed	2 (+
Seed addition	8 (+

Long-term removal of kangaroo rat[s] caused a dramatic change in habitat, fro[m] desert shrubland to grassland (Fig. 1). Effects of *Dipodomys* on vegetation were analyzed by ANOVA, not only comparing plot[s] where kangaroo rats had been removed t[o] plots where kangaroo rats were present, bu[t] also comparing transects inside and immediately outside the plots where kangaroo rat[s] had been removed (Fig. 2). Tall-statured perennial and annual grasses colonized th[e] open spaces between the shrubs and increased approximately threefold in the absence of kangaroo rats. Much of this response can be attributed to two species: the perennial *Eragrostris lehmanniana*, which increased more than 20-fold, and the annual *Aristida adscensionis*, which increased approximately threefold. There were complementary changes in two species of shor[t]

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nnual grasses (*Bouteloua aristidoides* and *B. arbata*); these were significantly less abun- lant where kangaroo rats had been re- noved. *Tridens pulchella*, a short-statured pecies and the only perennial grass that was :ommon on the site when the experiments vere begun, was the only abundant species hat did not show a significant response to kangaroo rat removal. The net result of excluding either all rodents or all three *Di- podomys* species for 12 years was a dramatic increase in the cover of tall grasses.

That kangaroo rats are a keystone guild in this ecosystem is further demonstrated by other changes that occurred on plots where they were removed. During the first 10 years after initiation of the experiments, large- seeded winter annual plant species had in- creased (Fig. 1), some by as much as several thousand times, and small-seeded winter annuals decreased on plots with rodents and kangaroo rats removed (*5, 7*). During this same period, seed-eating birds decreased their foraging on plots with rodents re- moved in comparison with plots where kan- garoo rats were present (*8*). This was asso- ciated with an increase in herbaceous (both grass and forb) vegetation and a decrease in the amount of bare ground, conditions that made it more difficult for the birds to harvest the available seeds. Six to 12 years after the experiment was begun, and in response to the increase in grass cover documented above, six species of rodents that are charac- teristic of arid grasslands differentially colo- nized the grassy plots where kangaroo rats had been removed (Fig. 3). Finally, we have noted, but not quantified, greatly increased accumulation of litter and longer persistence of snow on the plots where kangaroo rats were absent.

Two processes, seed predation and soil disturbance, appear to be responsible for the changes in this desert ecosystem that were caused by removing kangaroo rats. Selective foraging by kangaroo rats for large seeds is sufficient to explain the shorter-term re- sponses to our experiments (*5, 9*). Large- seeded winter annual plants increased in response to their release from rodent preda- tion, and asymmetrical competition from these dominant large-seeded species then caused the decrease in the small-seeded win- ter annuals. Increased availability of seeds and reduced competition from kangaroo rats may account, at least in part, for the colonization of kangaroo rat removal plots by the granivorous *Reithrodontomys* rodents (Fig. 3). Physical disturbance appears to have played the major role in the longer- term responses to removal of kangaroo rats. During their foraging, food caching, and burrowing activities, kangaroo rats make runways through the vegetation and move large quantities of soil, creating many shal- low pits and little mounds. This disturbance

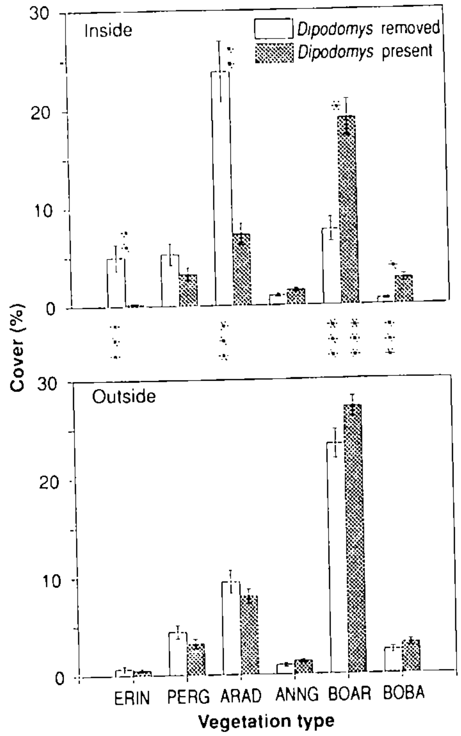

Fig. 2. Effects of removing kangaroo rats (*Dipodomys*) on densities of perennial and annual grasses. Plotted are mean values (±SE) of the percentage of cover for *Eragrostris lehmanniana* (ERLE), all other tall perennial grass species (PERG), *Aristida adscensionis* (ARAD), all other tall annual grasses (ANNG), and the short annual grasses *Bouteloua aristidoides* (BOAR) and *B. barbata* (BOBA). (**Top**) Data from transects inside plots where kangaroo rats were either present or removed; asterisks indicate significant differences between kangaroo rat removal and other plots. (**Bottom**) Data from transects immediately outside these plots. Asterisks indicate statistically significant differences between transects inside and outside plots where kangaroo rats were present or absent. (ANOVA, with plots as units of replication; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.)

Fig. 1. Photographs across the fences surrounding plots from which kangaroo rats were removed (left side of fence). (**Top**) Increase of the yellow-flowered, large-seeded annual, *Lesquerella gordonii*, 5 years after kangaroo rat removal. (**Bottom**) Increase in tall-statured annual and perennial grasses 13 years after kangaroo removal.

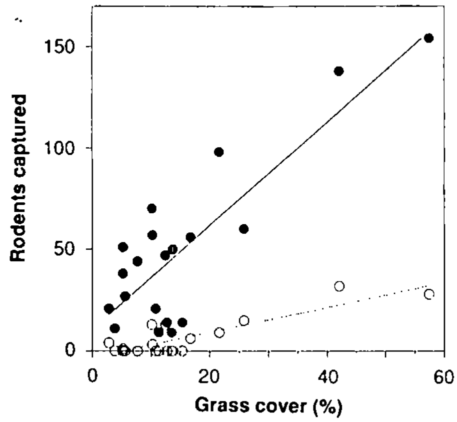

Fig. 3. Number captured per plot since 1983 of rodent species typical of grassland habitat as a function of mean percentage of cover of all tall perennial grasses plus *Aristida adscensionis*. Unshaded symbols represent only the most specialized grassland species, *Sigmodon hispidus*, *S. fulviventer*, and *Baiomys taylori*; shaded symbols represent the above species plus *Reithrodontomys* spp. Least-squared regression lines are fitted, and both are statistically significant ($P < 0.0001$).

may facilitate decomposition of litter, establishment of many annuals, and foraging of birds (*8*). Conversely, the reduction in soil disturbance following exclusion of kangaroo rats promoted the establishment and persistence of tall grasses, and this in turn favored colonization by specialized grassland rodent species.

Although kangaroo rats presumably cause size-selective seed predation and extensive soil disturbance wherever they are abundant, the kind and magnitude of changes reported here would probably not be duplicated if kangaroo rats were removed from different kinds of desert habitats. Our experimental site is near the zone of natural transition from desert to grassland, so that certain abiotic conditions or the presence or absence of keystone species can cause a shift between alternative vegetation types. Elsewhere in the southwestern United States grazing by domestic livestock is known to cause degradation of arid grassland to desert shrubland (*10*). At our site, however, the effects on vegetation of the exclusion of kangaroo rats in combination with livestock exclusion were much greater than those produced by the exclusion of cattle and horses alone. Grazing livestock were excluded from our entire 20-ha site since 1977, but no significant change in vegetation has yet been detected across the fenceline (*11*).

In the present case the "keystone" organism whose removal caused large changes in ecosystem structure and dynamics was not a single species, but a guild of three taxonomically related and ecologically similar kangaroo rat species. Removal of the largest and behaviorally dominant of these (*D. spectabilis*) had significant effects on the abundance and distribution of other desert rodents (*4, 12*), but it required the removal of all three species to cause wholesale changes in vegetation. On the other hand, the eight common and several rare species of desert rodents that remained after kangaroo rats had been removed clearly did not play the same keystone role and were not able to prevent the conversion of desert to grassland.

Twenty-five years after the concept of "keystone species" was first introduced, examples have been found in a number of taxonomic groups and habitat types (*1, 3*). It remains, however, to develop a general conceptual framework that will predict which kinds of organisms play key roles in different kinds of ecosystems. Native species are increasingly being eliminated from local habitats and larger regions as a result of human activities. It is critical to develop a theoretical basis for assessing the effects of these species on ecosystems so that, if extirpation of keystone organisms cannot be avoided, their roles can be replaced by other native or exotic species or by active ecosystem management.

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Characterization of "Peak E," a Novel Amino Acid Associated with Eosinophilia-Myalgia Syndrome

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Epidemiologic studies strongly associate eosinophilia-myalgia syndrome (EMS) with ingestion of tryptophan containing a contaminant ("peak E"). Prior reports have suggested that peak E is the di-tryptophan Nα-aminal of acetaldehyde. Spectral and chemical studies now demonstrate that peak E is 1,1′-ethylidenebis[tryptophan]. This novel amino acid may be the etiological agent responsible for EMS, or it may be a marker of a still unidentified causal agent.

As OF AUGUST 1990, EMS WAS LINKed to 27 deaths and over 1500 cases (*1*). Epidemiological studies (*2, 3*) have associated EMS with the ingestion of L-tryptophan (Trp) produced by a single manufacturer, suggesting that a contaminant is responsible for EMS. Recently we reported the discovery of a contaminant (peak E) in the Trp samples consumed by EMS patients that was absent in the Trp consumed by asymptomatic controls (*3*). A significant association exists between the presence of peak E and EMS-associated Trp (*3, 4*). Two groups have previously reported that peak E is the di-tryptophan Nα-aminal of acetaldehyde (*4, 5*). We present chemical and spectral data which show that peak E is actually the isomeric 1,1′-ethylidenebis[tryptophan] (1).

Peak E was isolated by high-performance liquid chromatography (HPLC) (*3*). Fast atom bombardment–mass spectrometry (FAB-MS) revealed peaks at mass-to-charge ratios (m/z) of 157, 231 (base peak), and 435 ($[M + H]^+$). High-resolution FAB-MS gave a mass of 435.2041, consistent with the molecular formula $C_{24}H_{27}N_4O_4$.

The proton nuclear magnetic resonance (^1H NMR) spectrum of peak E in D_2O (*6*) was similar to that of Trp in terms of

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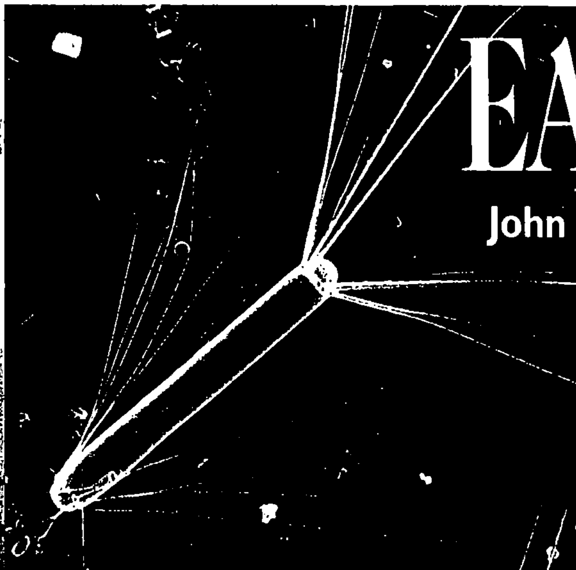
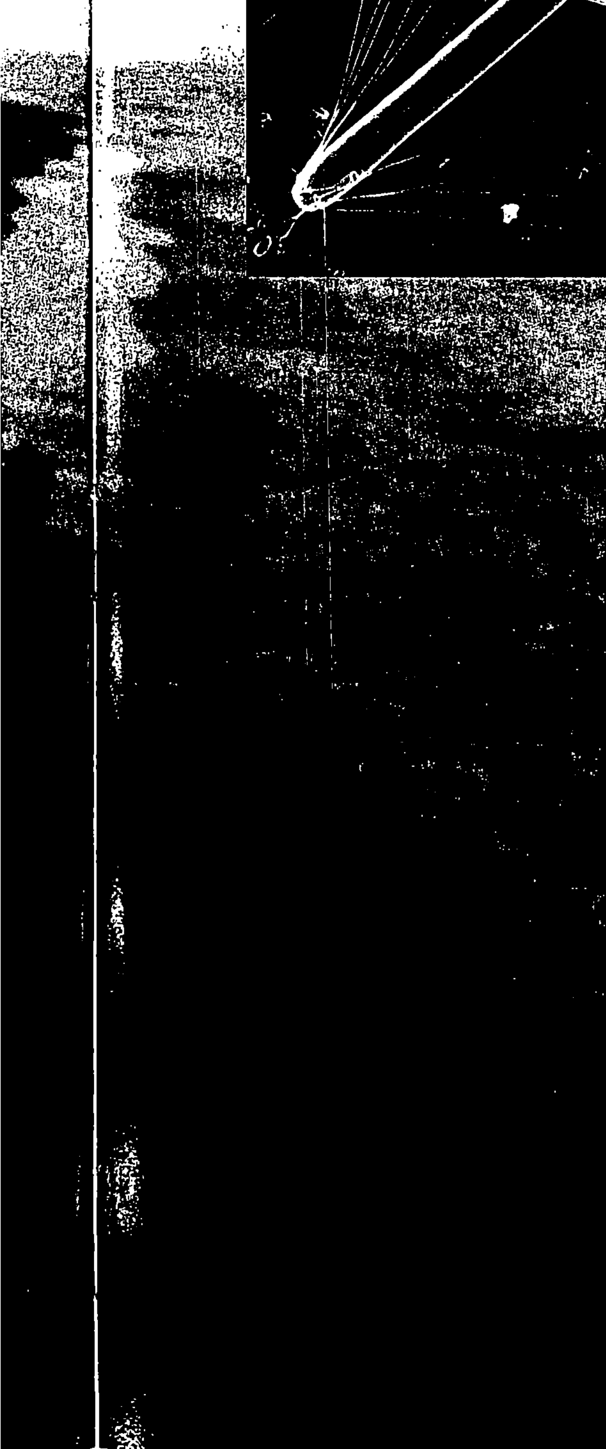


EARTH ON ICE

John Martin's idea is simple and ingenious, and some say it's crazy. If you dump iron in the ocean, he says, you can draw carbon dioxide out of the atmosphere—and cool down an overheating planet.

BY ROBERT KUNZIG



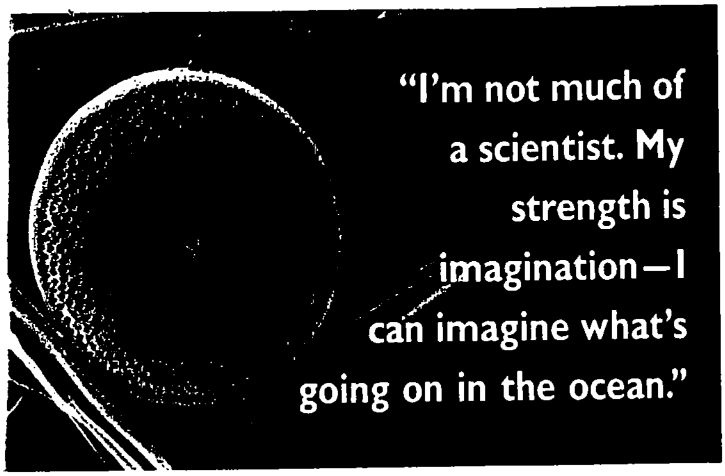
PHOTOGRAPH BY ANDY FREEBERG; MICROGRAPH BY DEE BREGER, LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

Moss Landing on Monterey Bay is a knot of antique stores and a harbor tight with boats that still fish the bay for albacore and salmon. From a distance, though, from the coast highway or from the artichoke fields of the Salinas Valley, what you see of Moss Landing are the twin stacks of the Pacific Gas and Electric power plant. They dominate the village like cathedral spires. And on a hot summer day, when air conditioners in central California are pumping furiously, the PG&E stacks are spewing 4,300 tons of carbon into the atmosphere. From the Moss Landing Marine Laboratories, which stand on the sand spit that protects the harbor from the bay, John Martin, the director of the labs, can gauge the region's demand for electricity just by looking up at the stacks. Martin thinks he may have a way of getting some of that carbon back out of the atmosphere. He says we might do it by dumping a few hundred thousand tons of iron into the ocean around Antarctica.

When Martin first made this suggestion a few years ago, he was half joking. "I got into this mess by shooting my mouth off," he says. But now he's in deep. Some people who heard about his idea got enthusiastic, and he is now pestered by people who have iron to get rid of. Others, particularly environmentalists, got mad. The National Research Council has convened two workshops on Martin's idea. The American Society of Limnology and Oceanography just held a special symposium for the second time in its history. Martin has appeared on *Good Morning America*. The upshot of these learned discussions is that Martin's idea may work or it may not; but it is certainly worth investigating, and it is certainly no joke.

Somehow this bluff, shy but outspoken man has managed to convince his peers that it is worth talking about fertilizing the Antarctic sea surface with a shipload of iron—that the single-cell algae that float there might grow like crazy and in the process draw carbon dioxide out of the atmospheric greenhouse. What accounts for Martin's persuasiveness? It is not charisma, though there is a disarming Yankee directness about him. And it is not just that everyone these days seems to want to talk about the greenhouse effect. The impact of Martin's idea really stems from its simplicity—and from the solid data that back it up.

John Martin at Moss Landing: Fertilize the ocean with iron, he says, and the phytoplankton—floating single-cell plants—will bloom. Inset: An electron micrograph shows a type of phytoplankton called a diatom; this one is relatively large—.001 inch long. More diatoms are on the following pages.



"I'm not much of a scientist. My strength is imagination—I can imagine what's going on in the ocean."

Dumping iron in the Antarctic, if it ever happens, would not be the weirdest project Martin has ever been involved in. In 1966, at age 31, he left the University of Rhode Island with a Ph.D. in oceanography and took a job with the Atomic Energy Commission. He was sent to Panama to work on Project Plowshare—the goal of which was to dig a second, sea-level canal through the isthmus by detonating a chain of 150 or so atom bombs. "What you do is, you set the devices up across Panama, and you touch them off, and it's just like a wave in the ground," says Martin. "You end up with a depression half a mile wide and banks on either side.

"But when you blow off all these underground shots, some radioactivity is going to fall out on the sea surface. And so they wanted to find out how much of this was going to be taken up by the food chain and eventually become a human health hazard. In the old days of atomic testing they used the 'specific activity' approach, which said, the more of a stable element there is to dilute the radioactive element, the safer you are. In other words, if you're a sea creature and you've got in the water an atom of radioactive zinc and a hundred atoms of stable zinc, the chances will be a hundred to one that you'll take up the stable element. So they wanted to know how much stable zinc was in the water, and iron, and all these other things."

Today Martin describes himself as an environmentalist, and he thinks nuclear power plants are dangerous. But two decades ago the idea of nuclear excavation didn't strike him as strange. "It didn't particularly bother me, I guess. Anyway, the bottom line was you have a big mountain range in Panama, and if you knocked down the mountain, it would have blown out every window in Panama City. So that kind of slowed them down. But it was an interesting project, and a tremendous amount of research came out of it."

Martin's own research involved taking samples of plankton—the sea's floating population of tiny plants and animals—from all over the Gulf of Panama and measuring their metal content. He found that the water and the plankton contained ample amounts of metals already, which suggested to the Atomic Energy Commission that a little radioactive metal wouldn't do much harm. Martin got pretty good at these measurements, or so he thought at the time. But in 1970, when he took a job at the Hopkins Marine Station, a Stanford outpost on the Monterey peninsula, he was tired of plankton ("They're cruddy things"), and he was tired of metals. He wanted to switch to something new.

A colleague pointed out that his timing was all wrong. The early 1970s were a time of swelling popular concern about the effects of heavy metals in the environment. Caltech geochemist Clair Patterson, in particular, was warning about the pervasiveness of lead pollution and the dangers of lead poisoning. The Roman Empire had fallen, he said, not to the Visigoths and the Huns, but to lead poisoning. Prodded by his colleague at Hopkins, Martin read Patterson's papers. They convinced him he should stay in the trace-metal business. When he moved to Moss Landing in 1972, he set up a trace-metals lab.

But Patterson proved to be a difficult role model. "About the mid-seventies," Martin recalls, "Patterson started telling everybody, 'Your numbers are all bad. You're contaminating your samples. When you try to measure lead in water or in plankton, everywhere you look or touch is contaminated with lead that's flowing out of exhaust pipes, and if you could put on this special pair of glasses, you'd see lead all over the room.' And Patterson is enough of a strong individual to go into a room full of scientists and say, 'You're all full of crap!' Then everybody would scream at him, 'You stupid old man!' He just completely infuriated a lot of people, and so they didn't want to believe him."

Martin and his assistants, though, decided to heed Patterson's advice. They started taking off their shoes before entering the laboratory so they wouldn't track in metal-rich dirt. They wrapped each bottle of seawater in three plastic bags. They kept the laboratory under positive pressure, with filtered air coming in and fans blowing out, so that no dust grains would waft in when the door was opened. They even switched to the brand of laboratory tissue that Patterson recommended as being particularly metal-free. "Our big goal in life," says Martin, "was to get one damn number for lead that Patterson would believe—in plankton, in sea lions, in water, or whatever. So we started doing all this, and it was amazing. All of a sudden all these things started to fall into place."

In Panama Martin had found that many metals were naturally abundant in seawater. Now he found that he had been wrong. When he cleaned up his procedures and eliminated sources of contamination, the water turned out to be a lot purer. What's more, such metals as were in it were distributed in an orderly way. Before, when researchers took samples of the water column at progressively greater depths, the concentration of a metal would fluctuate wildly and inexplicably. Now it followed a smooth profile, generally increasing toward the metal-rich mud on the bottom. Things made sense.

In the ensuing years Martin and his group measured lots of different metals. They measured manganese in seawater. They measured mercury and cadmium in sea lions, sea otters, and sewage. Those measurements were comparatively easy because there isn't much manganese, mercury, or cadmium floating around to contaminate a sample. Later Martin's group measured lead, which was harder; it was still being spewed out by cars running on leaded gasoline.

The biggest challenge of all, however, was iron. Martin had measured it in Panama, but those numbers, he had long since realized, were far too large. Iron is highly insoluble in seawater; it tends to glom on to organic particles and sink to the bottom. So the amount of iron in the water column had to be very small. But nobody had been able

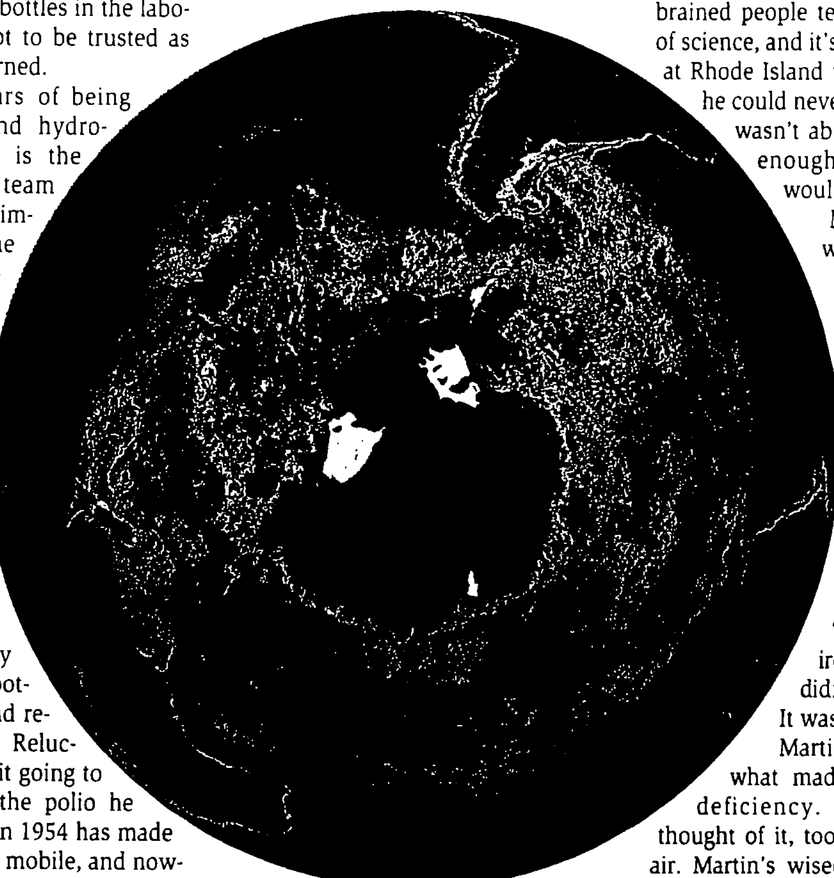
MICROGRAPH BY DEE BREGER, LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

PHOTOGRAPH COURTESY GENE FELDMAN, NASA/GSFC to say exactly how small, because contamination was almost impossible to avoid.

"Every time you get a speck of dirt, that's five percent iron," says Martin. "And of course man uses iron for everything. When you make a plastic bottle, it's usually extruded onto a stainless steel form—there's this hot plastic flowing over stainless steel, and some of that stainless steel is picked up in the plastic." Even the plastic bottles in the laboratory, then, were not to be trusted as far as iron was concerned.

But after ten years of being washed in nitric and hydrochloric acid—which is the procedure Martin's team follows with all the implements and even the walls in their all-plastic lab—a filthy, iron-infested bottle can get pretty clean. In a nutshell, that is the secret of how Martin's colleague Mike Gordon finally succeeded, in the early 1980s, in measuring the first reliable profile of iron in seawater: he finally had a clean enough bottle. By then Martin had retired from lab work. Reluctantly, he had also quit going to sea. Over the years the polio he contracted in college in 1954 has made him progressively less mobile, and nowadays he spends most of his time sitting down, either in a wheelchair or behind his desk. He has chronic pain. Gordon and another colleague, Steve Fitzwater, have taken over the hands-on work. It is slow, craftsmanlike work, and it requires dexterity. It is work that can be undone by a single errant dust grain.

"So Mike showed me this iron profile, casting pearls before swine," Martin recalls, "and I kind of ignored it." But then in December 1986, at a conference in San Francisco, he heard Bruce Frost of the University of Washington give a talk about an old problem in biological oceanography. In some regions of the ocean, such as the Antarctic, the floating single-cell plants, or phytoplankton, are notorious underachievers. Upwelling currents from the deep ocean bring them all the main nutrients—the nitrates and phosphates—they need to grow. Yet the nutrients go unused. The phytoplankton never bloom. That is, their population never explodes, as it does, say, in the North Atlantic, where the sea surface turns green each spring. Why? In his talk that day Frost offered the conventional explanations: there is not enough light in the Antarctic, he said; or it is too cold; or else the phytoplankton are kept in check by tiny, grazing animals, the zooplankton.



Phytoplankton already bloom in the Antarctic, as this satellite image shows (red and yellow), but chiefly near the coast.

PHOTOGRAPH COURTESY GENE FELDMAN, NASA/GSFC

It was after Frost's talk that Martin first decided to shoot his mouth off.

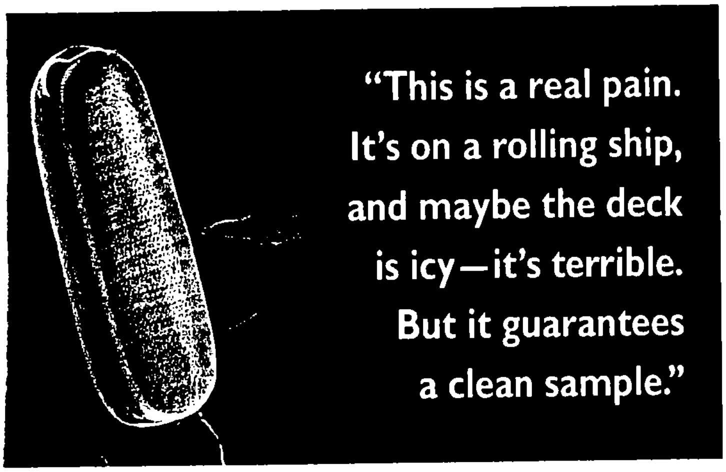
Martin is well liked by those who know him well; his assistants are former students who have stayed with him for years. The voice that sounds gravelly and short over the phone becomes gravelly and friendly and even self-deprecating in person. The eyes twinkle, and now and then they smile. There is a warmth to the man, although it doesn't bubble.

But Martin is also known for irritating his peers. It is not just that he is competitive. He doesn't seem to feel he belongs to the club. "I'm not much of a scientist," he says. "I don't have a very scientific mind—you know, math and all that. My strength is imagination—I can imagine what's going on in the ocean. I guess I'm right-brained. Right-brained people tend to get weeded out of science, and it's too bad. I knew a guy at Rhode Island who was brilliant, but he could never get his Ph.D. He just wasn't able to concentrate long enough on one thing. He would get bored."

Martin is impatient with complex analytic arguments. He likes simplicity. And he likes to needle people. So after Frost finished explaining how Antarctic zooplankton could keep the phytoplankton in check, Martin went up to him. "And more or less in jest I said, 'Aw, baloney, it's just iron deficiency.' And he didn't want to hear that. It was too simple."

Martin doesn't remember what made him think of iron deficiency. Other people had thought of it, too; the idea was in the air. Martin's wisecrack, though, was a kind of wishful boast—the wish being that the subject he had devoted his career to might prove important in some broader context. Back at Moss Landing he decided to try to deliver on his boast.

He knew that phytoplankton, like every other living organism, need iron to survive. Iron is an essential cog in the cell's synthetic machinery. Phytoplankton need iron to make chlorophyll, the molecule with which they capture sunlight. They need it to make nitrate reductase, the enzyme with which they reduce nitrate to a form suitable for incorporation into proteins. Most fundamental of all, they need it to make DNA, the stuff of their genes. So in principle it was possible for a phytoplankton population to be hobbled by a lack of iron.



"This is a real pain. It's on a rolling ship, and maybe the deck is icy—it's terrible. But it guarantees a clean sample."

Martin's problem, though, was that plankton get by on extremely small amounts of iron. Just how small is not known precisely. But the best estimate is that they use, at most, one atom of iron for every 10,000 atoms of carbon, every 1,500 atoms of nitrogen, and every 100 atoms of phosphorus. It didn't seem likely, on the face of it, that there could be areas where the phytoplankton had plenty of the nutrients that they need plenty of but were unable to bloom for lack of a few measly atoms of iron.

And yet Martin soon found evidence to back up his claim. It was buried among the debris on his chronically disorganized desk. Bob Duce, an atmospheric chemist at the University of Rhode Island and an expert on atmospheric dust, had recently sent him a paper. In it Duce estimated that more than half the iron in the open ocean comes from dust settling out of the atmosphere, as opposed to being upwelled from the deep with the other nutrients. Then Martin unearthed the iron measurements that Gordon had made on a cruise from California to Hawaii. Gordon's numbers suggested that, if anything, Duce was underestimating the importance of atmospheric iron: there was so little iron in the open ocean that about 95 percent of the plankton's requirements must come from dust.

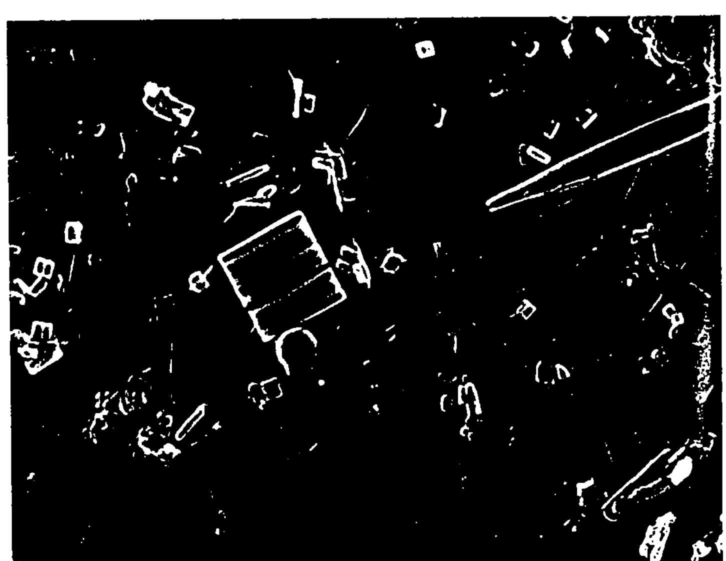
The circuit closed in Martin's mind: Where there's no dust, there's no iron. Except for shallow coastal waters, where the sea surface is close to the iron-rich mud on the bottom, the distribution of iron in the ocean is controlled by the geometry of winds and landmasses, particularly arid landmasses. In the equatorial Atlantic, for example, winds sweeping off the Sahara carry dust as far west as Barbados. All along that path there is no shortage of iron in the water.

But the winds that blow over the Antarctic cross almost no land that isn't covered by ice. So they drop on the ocean almost no dust and almost no iron. In the Antarctic and in other places far from dry land, Martin reasoned, phytoplankton would have to make do with what little iron was already in the water. And if Gordon's measurements from the cruise to Hawaii were representative, that was very little iron indeed—less than a millionth of an ounce in a cubic yard of seawater. Even for a frugal plankter, that's just not enough.

The thing to do, then, was to see whether Gordon's measurements held up elsewhere in the ocean. In the summer of 1987 Martin had a cruise scheduled to the Gulf of Alaska to make some manganese measurements. But manganese was old hat now. Martin's troops went after iron instead. They did the same sort of experiments they've been repeating in different places ever since. On each of these cruises Gordon and Fitzwater bring along their own clean mini-lab—it's the size of a small house trailer—and set it up on deck. They use special 30-liter sampling bottles that go through the sea surface closed (so the inside won't get coated with bilge water or fuel) and then snap open automatically at 30 feet. The bottle is lowered on Kevlar line, because ordinary steel wire might contaminate the water around the bottle. And when the bottle comes back up, now weighing more than 100 pounds, Gordon and Fitzwater either load it onto a plastic cart or manhandle it directly over to the clean lab—whatever they do, they don't let it touch the deck, because it might pick up a few atoms of iron that it would take back down on the next trip. "This is a real pain in the ass," says Martin, who goes to sea vicariously. "This is hard. It's on a rolling ship, and maybe the deck is icy—it's terrible. But it guarantees a clean sample."

With the clean samples they collected in the Gulf of Alaska, Martin's team did a simple experiment. They measured the amounts of iron and nitrate in the water and found that, according to the best estimate of phytoplankton requirements, the plankton didn't have enough iron to use all the nitrate. Then they divided the samples into two groups. One group they fertilized with iron; the other they left alone. They watched the bottles for four and a half days. At the end of that period the bottles with the added iron contained nearly nine times as much chlorophyll—a measure of the total mass of phytoplankton—than the unfertilized bottles. The idea that phytoplankton may be limited by iron deficiency had its first solid support.

This past year Martin's team went to the Antarctic—"the big enchilada," as he puts it. The Southern Ocean is 8 million square miles of nutrient-rich water fed by vigorous upwelling currents. Every year, during the six months of sunlight, phytoplankton bloom profusely in a narrow band along the Antarctic coast. Those blooms support vast herds of krill, shrimplike creatures that are in turn the daily bread of seals, penguins, and whales. Away from the



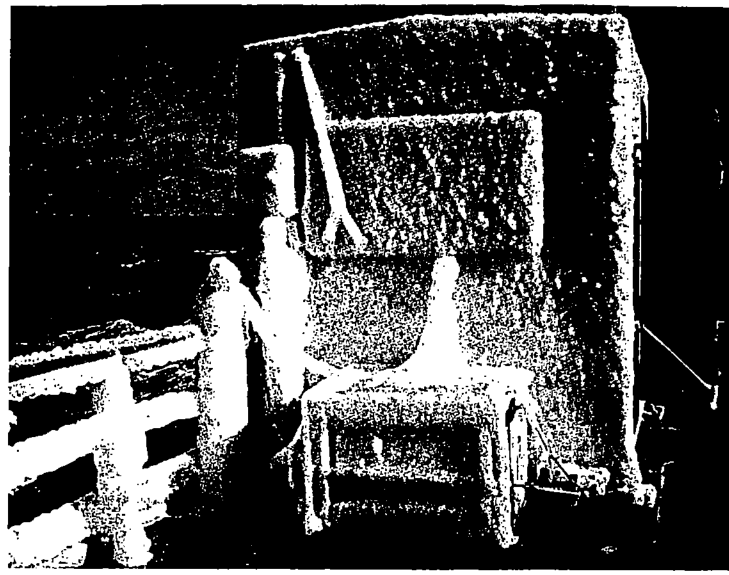
Far from the Antarctic coast diatoms are sparse . . .

MICROGRAPHS BY DEE BREGER LAMONT-DOHERTY GEOLOGICAL OBSERVATORY; PHOTOGRAPH COURTESY JOHN MARTIN coast, however, the Southern Ocean is much less fertile. The major nutrients are there, the temperature and sunlight are similar, but the plankton don't bloom.

Gordon and Fitzwater did iron-fertilization experiments in the Ross Sea, near the McMurdo base. They found that adding iron to a bottle of seawater taken from near the shore didn't help the phytoplankton much. That made sense; there was already plenty of iron in the water. It came from the bottom mud, and from atmospheric dust that had fallen on the glaciers over many years and then got dumped in the ocean. But a few hundred miles offshore the story was different. When Gordon and Fitzwater added iron to a seawater sample there, they got a fourfold increase in the amount of organic matter in the bottle. "There was hardly any growth without iron," says Martin. "And with it the stuff really took off."

Now the evidence for Martin's iron-limitation hypothesis was strong. And in the world of biological oceanography, this was big news—a new paradigm, one oceanographer called it. But a new paradigm about phytoplankton was hardly enough to get Martin on television. There was one more step to take.

It was a logical step, and actually Martin had been referring to it all along in his papers. If adding iron to a bottle causes the phytoplankton in the bottle to bloom, then you ought to be able to fertilize the ocean itself. It wouldn't take very much iron to fertilize the whole Southern Ocean, because phytoplankton don't need very much. Martin did a back-of-the-envelope calculation. If 300,000 tons of iron were broadcast in the ocean surrounding Antarctica over a six-month growing season, he figured, it would allow the phytoplankton to convert all the available nutrients—including 2 billion tons of carbon—into new organic matter. Those 2 billion tons would come from carbon dioxide that had dissolved out of the atmosphere into the surface waters. In other words, they would come right out of our greenhouse.



On the Antarctic cruise Martin's clean lab got a little chilly.

Much of that carbon, Martin assumed, would sink to the bottom of the ocean—in the form of plankton corpses or plankton parts or fecal pellets excreted by the things that eat phytoplankton. Oceanographers know this carbon sinking goes on all over the world; they call it the biological pump. They don't really know how important it is. But they think that right now it may take as much as 3 billion tons of carbon each year—half of all the carbon we pump into the atmosphere annually with our power plants and cars—and put it out of harm's way in the deep ocean. All Martin suggests is that it might be possible to speed up the pump in places where, for lack of iron, it isn't running up to speed.

. . . but when iron is added to the water they multiply.

The pump may have worked faster before, he says. Bubbles of ancient air extracted from Antarctic ice cores reveal that the carbon dioxide level in the atmosphere has fluctuated with the advance and retreat of the ice sheets. During the Ice Age the carbon dioxide concentration was only 200 parts per million, compared with 280 parts per million in the nineteenth century and 350 today. The same ice cores show that the amount of dust settling onto the Antarctic—and hence the amount of iron—was up to 50 times greater during the Ice Age. The world was drier then, with vast deserts and stronger winds that carried dust out to sea. All that iron-rich dust, Martin claims, may have led to massive plankton blooms in the Antarctic, which pumped carbon out of the atmosphere, which made the world colder.

If Martin is right, the amount of iron in seawater—something he spent more than a decade learning how to measure correctly—has a decisive impact on Earth's climate. "You give me half a tanker full of iron," Martin said this past May, shooting off his mouth again, this time to a *Washington Post* reporter, "and I'll give you another ice age."

Martin wasn't recommending another ice age, of course, and he doesn't truly think he could deliver one. He was just trying to get a point across. "I don't waffle," he says. But for quite a while after that remark he almost wished he did.

Martin's idea has been attacked from all angles. If there were huge blooms of phytoplankton in the Antarctic during the Ice Age, for example, some evidence of them ought to be preserved in sediments on the ocean floor. The dominant type of phytoplankton today are diatoms, which have hard shells of opal. This past year researchers at the Lamont-

"I don't want to go down in history as Martin's Mistake—the guy who ruined the ecosystem."

Doherty Geological Observatory looked for opal in sediment cores from the Southern Ocean. They found plenty in recent sediments, but in Ice Age sediments they found almost none—just the opposite of what Martin would predict. "This is one of the big flaws in my hypothesis," says Martin. Perhaps, he says, the Ice Age phytoplankton were mostly soft-bodied species that don't fossilize, rather than diatoms.

Then there is the question of whether Martin's back-of-the-envelope calculations are at all accurate—whether iron fertilization would get rid of as much atmospheric carbon dioxide as he thinks. The Antarctic upwelling currents, it has been suggested, might keep most of the plankton-fixed carbon from sinking; then the carbon would be quickly recycled into the atmosphere by bacteria, which break down organic matter. If that is true, then dumping iron in the Antarctic would have only a negligible impact on the greenhouse effect. People who specialize in making theoretical models of the ocean are now arguing the point. Martin is not a modeler. He prefers to let them duke it out.

your work

The modelers do agree on two things, however. One is that iron fertilization would at best be a palliative—never a cure—for the greenhouse effect. Even if it worked perfectly, it would remove less carbon from the atmosphere each year than we are now putting in, not to mention what we have put in already. The other point of agreement is that iron fertilization would not be a one-shot deal; it would have to be repeated, year after year, until we stop burning fossil fuels. Nor would it be just a matter of pushing a few rusting cars over the side of a ship. The iron would have to be broadcast extremely thinly, a few millionths of an ounce per square yard, and a steady supply would somehow have to be maintained in the face of its natural tendency to sink out of the surface waters. Martin speaks vaguely of a supertanker with a huge fan on deck; iron dust coming up from the hold on a conveyor belt would be cast by the fan into the stiff Antarctic winds. Alternatively, he says, perhaps some sort of time-release pellets might work. No one really knows.

No one knows either what effect the iron would have on the Antarctic environment. The ocean would not turn to green mush, but iron fertilization might favor some species over others and thereby alter the food web in unforeseeable ways. Martin thinks the simplest outcome is the most likely one: the iron would produce more diatoms and more krill, which eat diatoms, and thus more seals, penguins, and whales. ("When I get real facetious, I say I'm not interested in the CO_2 problem, I'm interested in repopulating the world's whale stocks.") But it's also possible the iron would yield blooms of organisms that krill don't eat and that would outcompete the diatoms. In that case the krill-based food web would collapse.

Martin thinks all these concerns are valid. They are not his area of expertise, and he doesn't pretend to have the answers. He is not suggesting, he stresses again and again, that we dump iron in the ocean now. He is only arguing for focused research into the possibility.

The one criticism that gets under his skin comes from people who say he hasn't really shown that phytoplankton are limited by iron—from people, in other words, who question his data or his interpretation of the data. Perhaps, these people argue, adding iron to a bottle of seawater doesn't really make the phytoplankton grow better. Perhaps the bottle just didn't happen to include any of the large zooplankton, called copepods, that graze on the plants and keep their population in check. With no grazers, it would look like the plants had bloomed.

Martin responds, somewhat testily, that he has in fact seen copepods happily grazing in his test bottles. But the whole argument irritates him. "They take a very simple thing and make it complex," he says of these critics. "And if you get into complexities, you can make all these arguments. If you keep it simple, you just say, 'Hey, I got two bottles, right, and in this one I'm going to put a little bit of iron and in this one I'm not. And I'm going to sit here and watch it for a week and see what happens.' And at the end of the week you hold it up to the light and you can see all these glinting cells. And this one over here, the one without iron, has nothing in it. To my way of thinking you have a very dramatic effect."

Martin would like to stop arguing. He would like to start preparing for what he considers the ultimate test of his hypothesis: fertilizing a small square of ocean, perhaps 60 miles on each side. It would take a couple of years, as he sees it, to thoroughly research the test area, to map its currents and its weather patterns and its patterns of life. Only then would the crop dusters or military cargo planes come in and start spraying iron. Meanwhile squads of oceanographers would be waiting on ships to monitor the effects.

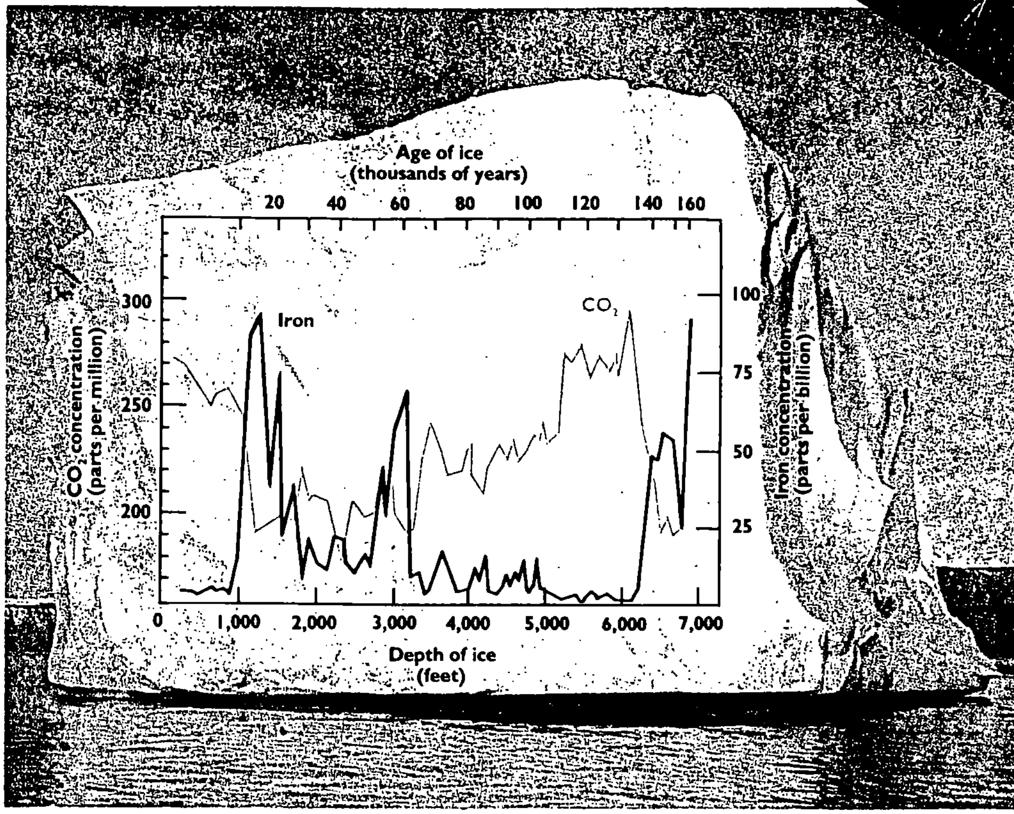
The experiment would not come cheap—it would certainly cost tens of millions of dollars, and perhaps more than a hundred million. The funding agencies are wary. But in spite of all the flak Martin has taken, support for such a test seems to be growing among his fellow oceanographers. In the end his data are hard to ignore.

Yet in the end there is also an argument against iron fertilization that no amount of data can answer. There is something fundamentally wrong, some people would say, with the whole idea that we should attempt to "fix" nature on so grand a scale. Wrong because we will surely foul it up; wrong because it is not our place. Does Martin not commit the sin of pride?

"We're already involved in the biggest experiment ever," Martin responds. "We're finding out what's going to happen if we dump three billion tons of CO_2 into the atmosphere every year. That is the biggest manipulation of the environment ever. What I argue is we're going to keep doing this. And we'd better know about ways, if we have to,

MICROGRAPH BY DEE BREGER, LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

Over the past 160,000 years, whenever the amount of iron-rich dust falling onto the Antarctic has gone up, the amount of carbon dioxide in the atmosphere has gone down, and vice versa. The data come from a 7,000-foot-deep Antarctic ice core; the deeper the ice, the older it is. The iron peaks at about 18,000 and 160,000 years ago correspond to ice-age peaks. Martin thinks dust falling out of the atmosphere caused Antarctic phytoplankton to bloom, taking up carbon dioxide and cooling the planet.



PHOTOGRAPH BY BRIAN VIKANDER/WESTLIGHT; GRAPH DATA PROVIDED BY JOHN MARTIN

to take CO_2 out of the atmosphere.

"The Chinese are not burning their coal right now, but they have massive reserves. As they industrialize they're going to want to use that coal. They're not going to say, 'Gee, gang, we're going to use solar power so we don't put out greenhouse gases.' The average Chinese peasant wants to have electricity and a refrigerator and maybe a motorbike—these people want to have the same crap we've got, and they're going to use what they've got available. CO_2 is not going to go down next year, or level off next year. It's going to go up by at least three billion more tons, and the next year three billion more and probably five. So by sixty years from now, you may be going up ten or fifteen or twenty billion tons a year. The purists say iron fertilization is crap, and we shouldn't even think about it—we should be conserving. That's very true. But what if we get into a situation where global warming really does occur?

"I'd see an ethical problem if we could go down and fertilize the Antarctic and remove the CO_2, but in the process we would kill all the whales and the penguins. Then I'd say, 'Don't do it. Man has created this, he can stew in his own juice. Leave the whales alone.' But on the other hand, if it turned out that you could go down there and add the iron and not disturb the environment, then I'd say go ahead and do it."

Martin hasn't been spending much time at Moss Landing lately. The earthquake in October 1989 destroyed his laboratories—pulled the rug right out from under the low stucco building, damaging it so heavily it had to be condemned. Martin and most of the other researchers have moved to Salinas, into temporary quarters provided by San Jose State University. But Gordon is still at Moss Landing, doing iron analyses in the shadow of PG&E; he's set up a clean lab in a trailer with equipment salvaged from the ruins. "We were very lucky," says Martin. "No one was hurt, and we didn't lose any of our equipment or samples. You lose your data and you're out of business."

It's now three decades since Martin first got interested in trace metals. That was back in graduate school, when he read about sheep in Australia whose wool fell off because of vitamin B_{12} deficiency. The deficiency was traced to a lack of cobalt, and it was cured by adding tiny amounts of cobalt to each acre of pasture. It was also back then that Martin learned about Justus von Liebig, the nineteenth-century German chemist. Liebig discovered the law of the minimum, which states that a plant will not grow unless it has its minimum requirement of each essential nutrient.

Liebig's law has always fascinated Martin. Now he thinks he has discovered the first marine example of it, and he would like very much to prove it conclusively. The iron-fertilization idea, he hopes, will help convince the public, his peers, and the funding agencies that the work is important. But Martin admits that it makes him a little nervous.

"It's scary," he says. "I don't want to go down in history as Martin's Mistake—as this guy who advocated adding iron, and they did it, and it completely ruined the ecosystem. What I want is to do the ocean experiment, and prove that iron is limiting—and then retire.

"When you work with trace elements, you'd like to think they're really important. But then you say, 'Who are you kidding—they're not important.' These are the conversations you have with yourself. And then, all of a sudden: 'Jesus! It looks like it is important. What the hell do I do now?' " ❑

Senior editor Robert Kunzig wrote "The Man Who Weighs Dinosaurs" in the October issue.

not

global

April 22, 1991

In my opinion,

Discover Magazine
3 Park Avenue
New York, N.Y. 10016

To the Editor:

John Martin proposes iron fertilization of the Southern Ocean as at least a partial solution to the threat of global warming. ("Earth On Ice", April 1991). He's got it exactly wrong. Our manhandling of the environment created the problems we face; it ~~in no way~~ is part of the solution.

It would be easy to attack Martin's suggestion on technical grounds: There is evidence that iron is not the limiting nutrient in the oceans; very recent research shows that, even if adding iron would increase plankton populations, the net amount of carbon sequestered would be modest; massive amounts of money and other resources would have to be mustered if the program were to be even <u>marginally</u> successful in achieving its objectives.

hubris

fundamental

But my opposition to Martin's suggestion runs much deeper. The proposal is dangerous because it plays to wishful thinking that there is no need for change; and that, with a little creative engineering, we can out-smart nature once again. The truth, however, is that we cannot, without serious repercussions, continue our campaign of re-creating the environment. in the design of our civilization;

You would think we would have learned that lesson by now. This is certainly not the first time we have undertaken such technological "fixes". Our determination to produce crops in areas not suited to produce them, for example, has poisoned the soil and, in some areas, created vast deserts of salt and pesticides. And consider our desire to adorn ourselves cheaply in silk by bringing gypsy moths into the country -- vast stands of diseased and dying trees are the legacy of that venture. The kudzu vine that chokes native plants and trees in the Southeast; the rabbits that overran Australia; and the brown trout that threatened the entire Yellowstone Lake ecosystem, are all testimony to our inability to gauge and control the effects of ~~our~~ grand eco-engineering schemes. And those were nothing compared to this proposal.

This was illegal

It is time we stop kidding ourselves. The simple truth is that it is only by changing our behavior -- and ~~not by further changing our environment --~~ that we can effectively address the global environmental problems we face. Study after study tells us we can make make significant gains at minimal cost with existing technologies. The need for such action is clear. The ozone layer is being depleted at an alarming rate; we need to move quickly to end the use ozone destroying chemicals. We continue to experience record warmth, severe drought,

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introduction of Africanized bees

of

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other warning signals consistent with those long since predicted to accompany! onset of global warming and climate change

extensive forest fires, and ~~intense storm activity;~~ We need to cut our emissions of greenhouse gases in every sector of the economy. The very threads of life are being severed as rampant deforestation drives thousands of species to extinction; we need to preserve and protect sensitive ecosystems and manage our forests sustainably.

So let's get on with it. I challenge our scientists to use their insights and creativity to devise ways for us to live in harmony with nature -- rather than speeding us further along the collision course ~~that~~ we ~~have already begun to travel.~~

are currently travelling

on