

Policy Implications of Greenhouse Warming

Mitigation, Adaptation, and the Science Base

Panel on Policy Implications of Greenhouse Warming

Committee on Science, Engineering, and Public Policy

National Academy of Sciences
National Academy of Engineering
Institute of Medicine

NATIONAL ACADEMY PRESS
Washington, D.C. 1992

Geoengineering

In this chapter a number of “geoengineering” options are considered. These are options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry. Most of these options have to do with the possibility of compensating for a rise in global temperature, caused by an increase in greenhouse gases, by reflecting or scattering back a fraction of the incoming sunlight. Other geoengineering possibilities include reforesting the United States to increase the storage of carbon in vegetation, stimulating an increase in oceanic biomass as a means of increasing the storage and natural sequestering of carbon in the ocean, decreasing CO₂ by direct absorption, and decreasing atmospheric halocarbons by direct destruction. It is important to recognize that we are at present involved in a large project of inadvertent “geoengineering” by altering atmospheric chemistry, and it does not seem inappropriate to inquire if there are countermeasures that might be implemented to address the adverse impacts.

Our current inadvertent project in “geoengineering” involves great uncertainty and great risk. Engineered countermeasures need to be evaluated but should not be implemented without broad understanding of the direct effects and the potential side effects, the ethical issues, and the risks. Some do have the merit of being within the range of current short-term experience, and others could be “turned off” if unintended effects occur.

Most of these ideas have been proposed before, and the relevant references are cited in the text. The panel here provides sketches of possible systems and rough estimates of the costs of implementing them.

The analyses in this chapter should be thought of as explorations of plausibility in the sense of providing preliminary answers to two questions and encouraging scrutiny of a third:

1. Does it appear feasible that engineered systems could actually mitigate the effects of greenhouse gases?
2. Does it appear that the proposed systems might be carried out by feasible technical means at reasonable costs?
3. Do the proposed systems have effects, besides the sought-after effects, that might be adverse, and can these be accepted or dealt with?

An exhaustive literature search and analysis has not been completed, but it has been possible to find useful material in the literature and to make first-order estimates that suggest positive answers to these first two questions. This being the case, it seems appropriate to continue consideration of the range of geoengineering possibilities and to pursue answers to question 3 above. In virtually all cases, there are significant missing pieces of scientific understanding.

Carrying the examination further would first require more detailed understanding, theoretical modeling, and simulation analyses of the physics, chemistry, and biology in the light of what is known about the geophysical, geochemical, climate, and ecological systems. If these further analyses suggest that the answers to the questions continue to be positive, experiments could then be carried out. These would not be full-scale climate mitigation experiments, but rather experiments intended to answer questions that might still remain after theoretical analysis, e.g., questions concerning optical effects and properties of various kinds of dust or aerosols, lifetimes and cloud stimulation properties of tropospheric sulfate aerosol, and so on. There is also a need for more detailed design, development, and cost analysis of the proposed deployment systems, perhaps including experimentation with specific hardware for deployment. Such work would give much more information with which to decide whether such systems could be deployed at a reasonable cost, and whether they would be likely to work as suggested by the preliminary evaluations included below.

If the theoretical analyses, experiments, and development work show that these mitigation ideas continue to have promise, the possibility of actual deployment would raise additional issues. The global climate and geophysical, geochemical, and biological systems under examination are all highly nonlinear systems involving the interaction of many complicated feedback systems. Such systems are likely to exhibit various forms of instability, including dynamic chaos, as well as various unintended side effects. These possibilities must be seriously considered before deployment of any mitigation system, and the risks involved weighed against alternatives to the proposed system.

Would attempts to mitigate greenhouse warming using one of these geoengineering systems result in putting a global system into some unintended and undesired state? Effects that have been suggested as possible

results of greenhouse warming itself, and which might result from attempts to mitigate it, include a shift to a glacial state and major shifts in ocean currents.

Our current models and understanding of geophysical systems do not allow us to predict such effects. Our understanding and modeling have so far not even permitted us to make a map of the possible states of the system. We might require a different modeling approach even to be able to do so.

It can be argued that, in the face of such uncertainty, we should not consider “tinkering” with the only earth we have. However, we are not entirely without understanding of this matter. The principal characteristic of chaos instability, for example, is that the behavior of states with only slightly different initial conditions may be totally different. This is frequently expressed by the statement that “the alighting of a butterfly may change the future of the earth.” However, in the sense that we know something of the effects of various kinds of events on parts of the geophysical system, we do know a good deal about this.

For example, we know something of the effect of the dust and aerosols resulting from volcanic eruptions on the climate system and on atmospheric chemistry, and we know something of the effect of industrial sulfur emissions on the climate system. It seems reasonable to assume that mitigation systems that put dust or aerosols into the atmosphere at altitudes and in quantities that are within the bounds of the natural experiments or of previous experiments would not produce instabilities or effects that had not been produced before. This expectation could provide one criterion for use of a geoengineering option: the activity must be within the natural variability of the geophysical system. We could use natural variability, or what are effectively previous experiments, as tests of the stability of the geophysical system and as opportunities to search for possible side effects. However, we must also consider that the chemistry of the atmosphere is changing, particularly from the injection of chlorofluorocarbons (CFCs) and from the increased injection of other greenhouse gases, so past chemistry will be an incomplete guide to the future. We can use the past and our understanding of the nature of the physics and chemistry to guide us in looking for new effects as natural events occur: the next significant volcanic eruption, for example, can be used as an opportunity to extend our understanding of the effects of dust, sulfuric acid aerosol, and chemicals produced by volcanic eruptions on stratospheric chemistry and the climate system.

The possibility would have to be taken into account that a natural event occurring during a mitigation activity could push the system beyond its normal bounds. For example, a large volcanic eruption occurring while artificial volcanic dust was in place might result in a dust loading beyond that previously experienced. Given some knowledge of the statistics and occurrence of eruptions (but noting their current unpredictability in detail)

and of the lifetime aloft of the dust or aerosol in question, it should be possible to make a reasonably prudent statistical design for such a mitigation system and to compare its risks with other alternatives.

In many simple nonlinear systems the phenomenon of hysteresis is observed. In these cases, as some physical variable is changed, the system changes its state in a particular way, but if the same physical variable is then returned to its initial value, the system does not retrace the path; it changes state along a different path. Thus attempting mitigation by decreasing the quantity of greenhouse gases in the atmosphere could, in principle, lead the system into a region of instability even though increasing them had not done so. The problem we face is that, given that the climate system is nonlinear and that we do not understand its state space, all actions can potentially lead to instability, and even a small-scale action is not necessarily less likely to do so than a large-scale action. Because of the possible sensitivity of geophysical systems to chaotic instability, we must proceed with caution in any geoengineering effort. We have to compare the nature and size of proposed actions with what we know about what has already been observed to occur in the system as a result of similar stimuli to it. This gives us a way of testing proposed actions. We can also try to learn the structure of the state space of the geophysical system by theoretical, modeling, and simulation analysis combined with observation of the system and its history, perhaps using small stimulus experiments that we believe to be safe to add to our understanding. While geological history provides evidence of what appear to be major changes in state, there is a great deal of observed variation in the system and in stimuli to the system that do not appear to result in changes of state.

Improving our understanding of these matters in this way may enable us to make rational decisions on what risks to take if we desire to use geoengineering or other means of mitigation to counter any greenhouse warming produced by greenhouse gas increases. Particular caution must be exercised because although changing atmospheric chemistry and changing global reflectivity may both have an impact on global mean temperature, the relevant physics for each is very different. The geographic distribution of effects may also be very important.

The kinds of steps that may be taken include the following:

- Theoretical modeling and simulation analyses of the physics, chemistry, and biology of the relevant geophysical, geochemical, climate, and ecological systems.
- Study of the potential for induced instability and chaos.
- Small-scale mitigation experiments to determine physical, chemical, and biological properties where these are unknown.
- Detailed design, development, and cost analysis of proposed deployment systems.

- Study of related natural events to understand their relevant properties, including the statistics of their occurrence.
- Study of possible ecological, geophysical, geochemical, and atmospheric side effects, including considerations of reversibility.

REFORESTATION

Reforestation is one possible method of slowing the buildup of CO₂ in the atmosphere. While some countries are a source of emissions because of deforestation (as discussed in Chapter 27), most temperate countries (such as the United States) are a net sink of emissions in that new growth at least compensates for trees harvested. This analysis focuses on the opportunities for rural reforestation in the United States. Urban reforestation is discussed in Chapter 21. It should be noted that uncertainties regarding land availability and cost make extrapolation from the few available figures difficult.

Reforestation efforts are relevant to the mitigation of greenhouse gas emissions because during photosynthesis green plants take in CO₂ and release oxygen. The carbon "fixed" during photosynthesis in excess of that released during respiration is stored in plant tissue. For perennial species such as trees, the amount of stored carbon can accumulate for decades. Therefore reforestation could potentially take in (or sequester) some of the CO₂ the United States generates from energy sources.

Recent Trends

Forests cover about one-third of the earth's land surface, stretching from evergreen forests in the moist tropics to vast boreal forests in the subarctic. Terrestrial biota and soils are an important part of the carbon cycle. They store 2,280,000 Mt (2,280 petagrams) of carbon compared to the 750,000 Mt (750 petagrams) of carbon in the atmosphere (World Resources Institute, 1990).¹ Although it should be noted that the amount of carbon stored in the ocean and lithosphere is much larger than that in either the atmosphere or the land, the time scales over which they equilibrate with the atmosphere are very large.

The land area of the United States has lost close to 25 percent of its forest cover since settlement of the North American continent began, and forest cover continues to decline. This is notwithstanding the planting of more and more trees over time (Figure 28.1). The 1989 decrease in tree planting is due to a decline in planting under the Conservation Reserve Program (CRP). In 1989, tree planting increased on National Forest and other federal lands, but decreased on private, state, and nonfederal public lands. A breakdown of total planting and seeding by ownership category in 1989 is given in Table 28.1; private sources planted 85 percent of the trees

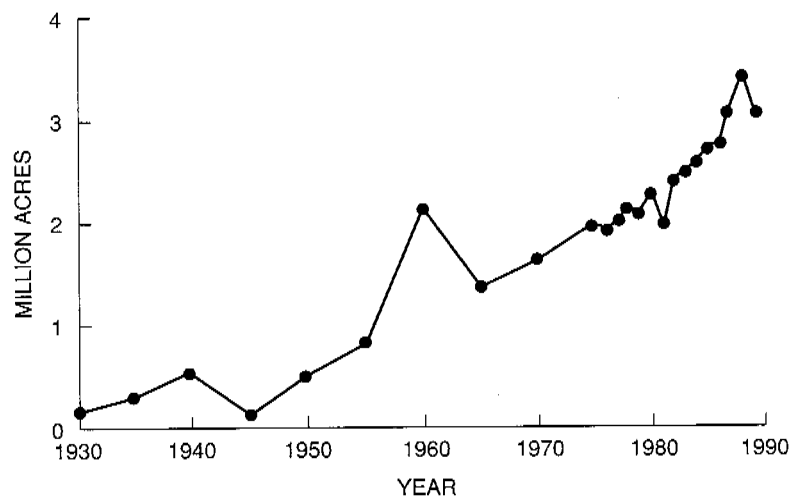


FIGURE 28.1 Historical summary of U.S. forest planting.

SOURCE: U.S. Forest Service (1990).

TABLE 28.1 Total Planting and Seeding by Ownership Category in FY 1989

	Acres	Percent of All Planting
Federal government		
National forests	307,138	10.2
Department of the Interior	52,006	1.7
Other federal agencies	9,257	0.3
TOTAL	368,401	12.2
Nonfederal public		
State forests	57,133	1.9
Other state agencies	6,013	0.2
Other public agencies	13,515	0.4
TOTAL	76,661	2.5
Private		
Forest industries	1,248,565	41.3
Other industry	22,225	0.8
Nonindustrial owners	1,306,096	43.2
TOTAL	2,576,886	85.3
GRAND TOTAL	3,021,948	100.0

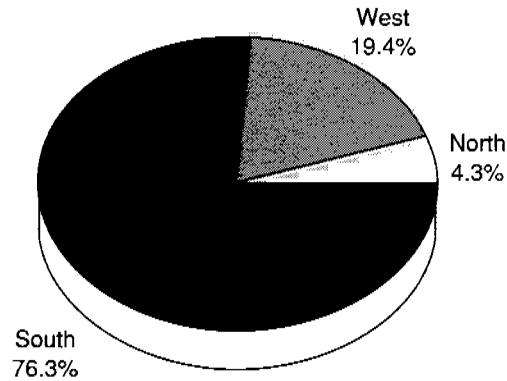


FIGURE 28.2 Total planting and seeding by region in FY 1989.

SOURCE: U.S. Forest Service (1990).

in the United States in that year. Figure 28.2 shows that the great majority of planting (76.3 percent) is in the southern United States (U.S. Forest Service, 1990).

Storing Carbon in Trees

Forests take up carbon fastest during their early years of rapid growth (which may be up to 80 years for some species). As trees age, their growth rates decline and the rate at which they sequester carbon also declines. As a result, stands of young trees, on a net basis, actively increase stores of carbon (per unit area) more rapidly than mature forests, where photosynthesis is more closely balanced by respiration and death. On the other hand, a mature forest generally contains more stored carbon overall than a younger forest does.

The ability of a particular type of tree to store carbon depends on a number of factors, including its intrinsic growth rate as well as site and stand attributes. Carbon is stored in stemwood, branches, and roots, and in the soil around the tree. Carbon incorporated in leaves is recycled rapidly, often on an annual basis, and thus is less important from a carbon storage standpoint.

Researchers have documented drastic improvements in the present net productivity (carbon uptake) of several species of trees. Heilman and Stettler (1985) managed short rotations of hybrid cottonwoods on fertilized, irrigated plots in western Washington and achieved nearly 14 t of carbon uptake per hectare (ha) per year of total production. A study by Steinbeck and Brown (1976) of intensely managed American sycamores on a 4-year rota-

tion in Georgia yielded a carbon uptake of 6.5 t C/ha/yr. On the average, however, Marland (1988) estimates that U.S. commercial forests have an uptake of roughly 0.82 t C/ha/yr. If they were fully stocked, the average forest's productivity could increase to 1.35 t C/ha/yr. In sum, both the species of tree and the management practices are important considerations in reforestation policy, as are the kinds of land on which the trees are planted and the climatic zones in which planting occurs. Therefore a reforestation strategy for sequestering carbon might theoretically involve the use of fast-growing species with advanced silviculture techniques on optimal sites. However, there is a trade-off between maximum carbon storage and maximum rate of carbon uptake. For example, in the sycamore experiment mentioned, trees were harvested every 4 years to maintain the high growth rates of young vigorous plants. These data on short-rotation forestry demonstrate that rates of carbon uptake can be dramatically increased by forest management strategies. For net U.S. carbon emissions to be reduced, trees must be either protected from oxidizing to CO₂ or used to replace fossil fuel burning. In general, more intensive management requires more energy inputs, and these must be compensated to determine net carbon benefit.

The most comprehensive analysis of the potential for sequestering carbon in trees in the United States is that undertaken by Moulton and Richards (1990) of the U.S. Forest Service. This is a detailed analysis of the land available in the United States that could support trees, the carbon uptake that might be expected, and actual costs for each type of land to be managed. According to Moulton and Richards, it is possible to sequester up to 720 Mt C on economically marginal and environmentally sensitive pasture and croplands and nonfederal forestlands. After analyzing the potential carbon uptake and cost per ton in 70 region and land-type classes, Moulton and Richards arrange these in order by cost per ton and assemble a supply curve for carbon sequestering. The analysis concludes that up to 56.4 percent of U.S. CO₂ emissions could be sequestered in domestic trees at costs ranging from \$5.80 to \$47.75/t C.

Recognizing that the Moulton and Richards analysis suggests that 56.4 percent of U.S. CO₂ emissions could perhaps be offset with a massive commitment to a reforestation program, the Mitigation Panel takes a very conservative approach in estimating the carbon offset that might be envisioned. As discussed in Appendix P, the Mitigation Panel's analysis accepts that the 10 percent objective described by Moulton and Richards is a reasonable initial target and that reforestation of economically marginal or environmentally sensitive pasturelands and croplands and nonfederal forestlands to a total of 28.7 Mha could take place at costs as described in their analysis.

Several factors in the Moulton and Richards analysis, however, heavily influence the numeric results and are likely to elicit some discussion as to the magnitude and cost of reforestation. Their analysis has a 40-year time

horizon, so it does not confront the consequences of declining growth rates as trees approach maturity or of the long-term possibilities for tree maintenance or harvest. In addition, land rental rates and the ratio between carbon uptake in marketable timber and total ecosystem carbon uptake are somewhat uncertain. Taking these factors into account, the Mitigation Panel's analysis suggests that 240 Mt CO₂ equivalent per year could be sequestered at costs between \$3 and \$10 per ton of CO₂ (average cost is \$7.20/t CO₂). Demonstration projects could verify the lower costs and higher targets for total sequestration suggested by Moulton and Richards.

Obstacles to Implementation

There are several constraints on implementing a reforestation policy. First, there are land use commitments. For reforestation to be pursued on a large scale, planting would have to take place on marginal agricultural lands. This represents a long-term commitment to nonagricultural uses.

Second, there may be resource constraints (e.g., water). Great care and understanding would be required to select tree species, species mixes, and management strategies to maximize the potential of sites with widely different available resources.

Policy Options

Public policy decisions to increase carbon storage through reforestation involve such silviculture issues as replanting, selection of species to be planted, and land management practices such as fertilization. To implement these reforestation options, however, someone must pay for the reforestation itself and for the cost of maintaining land in forest cover. Landowners face a variety of alternative opportunities and liabilities. Policies to increase and maintain forests to store carbon must therefore address questions of economics as well as silviculture.

The cost of sequestration, considered apart from the value to be recaptured by sales of timber, ranges upward from zero. The economic cost—which can, of course, be negative if the investment in sequestration is less than the return from the sale of harvested products and other benefits—is determined both by the value of forest products and by the value of alternative land uses. Because forests have a biological time scale on the order of decades, significant uncertainty is the norm in economic analyses. Public policies can affect management choices by changing, for example, the taxes levied on timber harvest, the regulations that govern forest practices, or real estate taxes.

To ensure long-term sequestering of wood on private lands, governments may need to purchase title or limited property rights.

Other Benefits and Costs

Reforestation can have many other positive benefits, including enhanced biodiversity, wildlife, air and water quality, aesthetics, forest products, and recreational opportunities. Reforestation can also raise environmental concerns, and there is some apprehension about the implications if planting were to occur as broad expanses of monocultural plantations.

Research and Development

A recent National Research Council (1990) report entitled *Forestry Research: A Mandate for Change* provides a number of research recommendations relative to societal concerns regarding the relationship of forests and climate, biological diversity loss, forest product demand, "pristine" forest area demand, sustainable wood production in conjunction with environmental protection, and maintenance of forest health. The NRC Forestry Research Committee (1990) recommends

- improving understanding of the basic biology and ecology of forests,
- developing information to sustain productivity of forests as well as to protect their inherent biological diversity, and
- understanding the economic and policymaking processes that affect the fate of forests.

Conclusions

Reforestation has the potential to offset a large amount of CO₂ emissions but at a cost that increases as the amount of offset increases. This analysis recognizes the large land resource required and adopts a conservative approach with respect to the U.S. Forest Service analysis of the amount of carbon that might be sequestered. It also recognizes that forests will mature and that reforestation is thus an interim approach to the long-term concerns of greenhouse warming. In addition, if a forest is harvested, the only true CO₂ offset is the amount of carbon stored in soil, roots, and as lumber or other long-lived products. Furthermore, there is some apprehension about the implications for biodiversity if planting were to occur as broad expanses of monocultural plantations. Overall, however, reforestation seems to provide a method of storing carbon with little adverse societal impact and a number of benefits.

INCREASING OCEAN ABSORPTION OF CARBON DIOXIDE

The Approach

The oceans already play an enormous role in establishing planetary climate, both through the transport of heat and supply of water vapor and

through the absorption of a large fraction of fossil fuel CO_2 . Estimates of the net ocean sink for CO_2 range from the traditionally accepted value of some 40 percent of fossil fuel CO_2 emissions (through reaction of CO_2 gas with carbonate ion over the entire ocean surface, and based upon models derived from Oeschger et al. (1975)), which today gives close to 3 Gt C/yr, to the much lower value of 0.6 Gt C/yr recently reported by Tans et al. (1990). No realistic model of earth's climate can escape simulation of the oceans in some form.

While the oceanic role in moderating the present-day fossil fuel increase depends almost totally on the rate of mixing and the alkalinity, the potential future role of ocean biota cannot be neglected. The potential amount of total carbon that could be utilized by oceanic photosynthesis has been estimated to be 35 Gt/yr. However, this figure represents the gross fixation of carbon in the ocean; the net effect on the atmosphere will depend on the return flow from decomposition and will eventually reach steady state. Ice core records (Neftel et al., 1982; Barnola et al., 1987) show that in the past, the atmospheric CO_2 level has fluctuated independently of the activities of man, with ice age CO_2 concentrations some 30 percent lower than the most recent preindustrial value. A key question is thus, Can this state be achieved today?

In 1984, three independent research groups published hypotheses on this phenomenon (Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984). Each reached the conclusion that the key lay in the surface nutrient concentrations in polar ocean regions. In areas such as the far North Pacific and the antarctic circumpolar ocean, high concentrations of nitrate and phosphate (the key ingredients for plant growth) are unused. The problem did not seem to be insufficient light, or bitter cold, but some other variables not yet recognized. The 1984 models showed that if these nutrients were assimilated, the conversion of CO_2 to organic carbon could readily account for the ice age signal. These nutrients can be regarded as an important unused chemical capacity of the ocean, one of a scale to significantly affect the global carbon balance. A radical solution to this ice age CO_2 puzzle has been proposed by Martin and co-workers (Martin and Fitzwater, 1988; Martin and Gordon, 1988; Martin, 1990; Martin et al., 1990). These scientists achieved the first reliable measurements of "dissolved" iron, at the nanomolar level, in ocean waters through stringent avoidance of the all-pervasive contamination problem. They further showed that addition of trace amounts of iron to natural populations of phytoplankton stimulated photosynthesis, and they hypothesized that iron limited the phytoplankton growth in these areas. Thus trace inputs from atmospheric dust events could trigger blooms of the plankton and ultimately lower atmospheric CO_2 . Finally, the ice core record shows that glacial times, with dry and dusty continents, are characterized by strong dust input to oceans.

The route to contemporary utilization of this unused oceanic potential is

therefore direct: the addition of trace amounts of iron to vast areas of the ocean surface to stimulate phytoplankton growth has recently received widespread publicity. The tenuous nature of the hypothesis, the presence of other limiting factors, the discrepancy between the total ocean surface area involved in natural reaction with the atmosphere and the relatively small area (approximately 16 percent) of the ocean surface available for active manipulation of the iron concentration—all call for caution in expectations for this class of phenomena. Return flow of the products of decomposition of the fixed carbon negates the possibility of a one-time fix. However, this concept usefully raises issues of what must be considered in any discussion of active intervention in the oceanic carbon cycle. It was in this spirit that iron fertilization, along with the potential use of macroalgae to assimilate large quantities of CO₂, was examined in a recent National Research Council (NRC) workshop on Marine Algal Productivity and Carbon Dioxide Assimilation (October 31, 1990).

Phytoplankton specialists at the NRC workshop agreed that it is conceptually feasible to slow the increase in atmospheric CO₂ levels through enhanced new primary production in oceans, resulting in enhanced net transport of CO₂ from the atmosphere to the oceans. From existing models, they estimated that an additional 2 Gt C/yr can be removed from the atmosphere if new primary production is enhanced and most unused nutrients are assimilated. Because iron is required at concentrations in the nanomolar range, they projected the cost of iron fertilization to be low.

Cost Estimates

There are two bases for the cost of iron fertilization; one based on the work of Martin, and the other based on the NRC workshop mentioned above.

The work of Martin would indicate that fertilization of the entire southern ocean could be accomplished with only 0.43 Mt of iron (Fe) per year, the amount required to support the removal of 2 to 3 Gt C/yr (Martin, 1990). Martin gives no number for the area of ocean to be fertilized and suggests no specific chemical form for the iron.

The NRC workshop suggests that iron fertilization might remove an average of 1.8 Gt C/yr over a 100-year period. The workshop suggests an application of 1 to 5 Mt Fe/yr in the form of a solution of ferrous chloride (FeCl₂), "or perhaps in some other form," and gives the area to be fertilized as "approximately 18 million square miles."

A cost estimate will be composed of the cost of ships and ship operations, and the cost of the chemicals, with some allowance for overall system operations.

For estimating purposes a 1-million-square-nautical-mile area divided into

lanes 1 mile wide will be considered. This gives 1 million miles of steaming required each year.² Fifteen ships, each steaming 240 miles per day (at 10 knots) for 300 days per year, would travel 1 million miles. When replenishment time, and so on, is considered, we can specify 20 ships, each of 10,000-ton capacity, each replenished every 2 months.

If we assume \$100 million per ship, with each ship having a \$10,000 per day operating cost, we get a cost for the fleet of \$2 billion, giving an annual capital cost (amortized over 20 years) of \$0.10 billion and an annual operating cost of \$73 million. This gives a total annual operating cost for 1 million square miles of coverage of \$173 million. For 18 million square miles the system must be increased in size by a factor of 18, giving about \$3 billion per year. In the antarctic ocean we must give a generous allowance for weather contingencies; let us use a factor of 3, giving an estimate of \$9 billion per year for ship costs and operations. To this we may add \$1 billion per year for general system operations, giving an operations total of \$10 billion per year.

To the operations estimate we must add the cost of the iron fertilizer. The form of iron usually absorbed easily by living organisms is the ferrous form. The cheapest bulk ferrous iron compound easily available is ferrous sulfate. Martin's 0.43 Mt of iron is equivalent to about 1.2 Mt of ferrous sulfate, which can be purchased in bulk for \$10 to \$15/t (Chemical Marketing Reporter, 1991), for a total of \$12 to \$18 million per year.

Ferrous chloride, mentioned by the NRC workshop, is much more expensive than ferrous sulfate. It can be bought in bulk for \$220/t Fe in the chemical (Alfred M. Tenney, Eaglebrook, Inc., private communication to Lynn Lewis, G.M. Research, April 11, 1991). The NRC workshop requirement for 1 to 5 Mt Fe gives a ferrous chloride cost of \$0.22 to \$1.1 billion per year.

Thus the range of chemical cost may be between \$0.012 and \$1.1 billion per year. However, both ferrous sulfate and ferrous chloride are relatively cheap because they are the waste product of steel "pickling" with acid. The current North American availability of ferrous chloride is estimated to be about 150,000 tons of iron equivalent, and the world amount may be a million tons (Alfred M. Tenney, Eaglebrook, Inc., private communication to Lynn Lewis, G.M. Research, April 11, 1991). Thus it is not clear what the price of ferrous chloride might be in million- to multimillion-ton quantities per year. If we assume that the price will be less than 100 times the current price of ferrous chloride, we get a total range of cost for iron fertilizer of \$0.010 to \$100 billion per year.

Adding the operations cost to the fertilizer cost, we get a cost range of \$10 to \$110 billion per year. This will mitigate 1.8 to 3 Gt C (using the range from both Martin and the NRC workshop), equivalent to the mitigation of about 7 to 11 Gt CO₂/yr. This gives a final range of about \$1 to \$15/t CO₂/yr.

Further thought is likely to lead to simpler, more automatic, and cheaper means for the distribution of iron fertilizer.

Some Problems

Peng and Broecker (1991) argue that on dynamic considerations the scheme of fertilization by iron is unlikely to succeed as a continuing full-scale pump of CO₂ from the atmosphere into the ocean. They argue that vertical transport in the antarctic is sufficiently sluggish that the flow of CO₂ into the ocean from the atmosphere would rapidly saturate the surface waters with CO₂, and, since the circulation would not carry the saturated water away fast enough, the transfer of CO₂ from the atmosphere into the ocean would stop. This presumably would leave the storage of CO₂ (as carbon) represented by the standing crop of algae in place as long as the fertilization were to continue. They estimate that 100 years of fertilization would result in a lowering of the atmospheric CO₂ content by 30 ± 15 ppm. It is possible that small-scale experiments might be devised to test this by fertilizing a limited area for a period of time and studying the results. Recently reported observations by De Baar et al. (1990) suggest that iron may not be the sole limiting factor in antarctic phytoplankton growth.

In addition to using microalgae to assimilate CO₂, use of macroalgae (seaweed) has also been proposed. Advantages of macroalgae include a faster rate of sedimentation, as well as their value as a biomass fuel and a source of chemicals and feeds. Their use, however, would require an engineered system of production to achieve large areas of cultivation.

There are numerous questions to be answered pertaining to the use of both microalgae and macroalgae for CO₂ assimilation before better estimates of costs of carbon removal can be made for either system. Key aspects associated with cost projections include productivity rates in open oceans, nutrient recycle, micronutrient (especially iron) limitations, and the detailed design of a system for the controlled delivery of millions of tons of iron over large areas of open oceans.

As with other mitigation options, important environmental questions raised by the use of algae to assimilate CO₂ include those concerning food chain effects, the introduction and proliferation of nonindigenous species (especially for macroalgae), anaerobic decomposition of algae to CH₄, and the possible formation of large amounts of haloforms and dimethyl sulfide. As noted in the discussion of cloud stimulation below, the natural organisms whose growth would be stimulated by the addition of iron might be expected to produce dimethyl sulfide, which would form cloud condensation nuclei. At times and places of little cloudiness, the area fertilized might be expected to become more cloudy, which, might in turn have a further cooling effect. There is also concern about the possibility of creating an anoxic layer in the shallow subsurface.

SCREENING OUT SOME SUNLIGHT

Another option for mitigating a global warming would be to try to control the global radiation balance by limiting the amount of incoming radiation from the sun. This could be done by increasing the reflectivity of the earth, i.e., the albedo. Proposals for increasing the whiteness of roofs and surface features would have some effect, but only a fraction of incident solar radiation reaches the earth's surface and a purposeful change in albedo would have more impact if done high in the atmosphere. According to Ramanathan (1988), an increase in planetary albedo of just 0.5 percent is sufficient to halve the effect of a CO₂ doubling. Placing a screen in the atmosphere or low earth orbit could take several forms: it could involve changing the quantity or character of cloud cover, it could take the form of a continuous sheet, or it could be divided into many "mirrors" or a cloud of dust. Preliminary characterizations of some of the possibilities that might be considered are provided below.

Estimating Screen Parameters

The calculation here assumes the screen is a continuous sheet. Note that if the dust particles are of a size comparable to the wavelength of light, scattering effects will have to be taken into account.

Given the equatorial radius of the earth and a nominal low orbit of 222 km, the radius of the sphere in which the sheet, or parasol, is to be located is 6.6×10^3 km. Then the area of the sphere to completely wrap the earth is 5.5×10^{14} m². To compensate completely for the greenhouse warming from a doubling in the concentration of CO₂ in the atmosphere,^{3,4} the parasol must cover 1 percent of the area, or 5.5×10^{12} m².

If this parasol must be 1 micron (μm) thick, 5.5×10^6 m³ of material is required. At a density of 1 g/cm³, 5.5×10^9 kg would have to be lifted into low earth orbit. The cost of establishing such a project is dominated by the cost of putting the parasol into orbit. At an optimistic cost of \$1,000/kg, the cost of lifting the material into orbit would be \$5.5 trillion.⁵ Such a parasol would mitigate about 1000 Gt of carbon emissions, for a cost of about \$5.5/t C mitigated or about \$1.5/t CO₂ (rounding the number). At current launch costs of \$10,000/kg, the cost would be \$55/t C mitigated or about \$15/t CO₂.

The assumption that a 1 percent decrease in sunlight is equivalent to mitigating the greenhouse effect of 1000 Gt of carbon (or 4000 Gt CO₂) is key for all of the estimates that follow.⁶ Ramanathan's increase of 0.5 percent in planetary albedo quoted above as sufficient to halve the effect of a CO₂ doubling is used here and below as a 1 percent screening effect for estimating purposes. Using Figures 3.1 and 3.2 of the report of the Synthesis Panel (Part One), we see that the total change in greenhouse gases since

before the Industrial Revolution until 2030 may be equivalent to about 3.3 W/m², or slightly less than 1 percent of the 349 W/m² of solar insolation.

Space Mirrors

A single mirror would be unmanageable and would probably create problems in the regions where its shadow fell as it moved around the earth. However, a set of smaller mirrors might be considered, each maneuvered as a solar sail in earth orbit. By changing its angle to the sun (and hence the solar radiation pressure forces on it), the orbit of each sail could be controlled.

If each sail is 10⁸ m² in area (a large sail to manage), 55,000 such sails would be required. This appears to be a very difficult, if not unmanageable, control problem. However, if the requirement is for the mitigation of 8 Gt CO₂ equivalent (the 1988 U.S. emission of greenhouse gases), a parasol 500 times smaller in area, equivalent to 110 such solar sails, would be required. At the previous \$1.5/t CO₂ mitigated, the cost would be \$12 billion; at current launch costs, the cost would be \$120 billion.

The question of how often (because of damage to the sails resulting from debris collisions) sail replacement would be required has not yet been examined. If replacement of all of the sails were required each year, the figures above would be annual costs; the 40-year cost would be 40 times larger, and similarly for other replenishment rates. With this possibility in mind, by using previous costs of \$1.5 to \$15/t CO₂, costs may be estimated as in the range of \$0.1 to \$15/t CO₂/yr.⁷

Space Dust

The space parasol could be designed as an orbiting dust cloud. To minimize launch costs, very small dust particles are required. However, because of solar radiation pressure, small dust is driven out of orbit or into the earth's atmosphere in very short times; the particles are barely orbital (Mueller and Kessler, 1985). Peale (1966), quoted by Mueller and Kessler (1985), gives 1500 cm²/g, or the equivalent of aluminum oxide particles 3 μm in size, as the limit below which this sweeping effect gives dust a short lifetime. A reflecting cloud of fine dust in orbit does not appear to be practical, and the launch costs for large dust particles appear to be too high to be practical.

Stratospheric Dust

Although the space dust option does not appear to be sensible, computations of the residence times of 0.2-μm dust above 20 to 40 km are of the

order of 1 to 3 years (Hunten, 1975). It seems to be generally accepted that volcanic aerosols remain in the stratosphere for several years (Kellogg and Schneider, 1974; Ramaswamy and Kiehl, 1985). A screen could be created in the stratosphere by adding more dust to the natural stratospheric dust to increase its net reflection of sunlight.

An alternative to dust is sulfuric acid aerosol, the other principal natural component of stratospheric haze. Dust seems a better choice because it is similar to dust from natural soil and so should have no noticeable effect on the ground as it gradually falls into the troposphere and rains out. (Other possible effects are referred to below.) However, Budyko (1982) suggests the use of sulfuric acid aerosol, to be created by the burning of sulfur in situ, resulting in sulfur dioxide (SO_2), which will automatically absorb atmospheric water to result in droplets of sulfuric acid solution. He gives the required tonnage of sulfuric acid to reduce the total radiation by 1 percent as 600,000 t. As we will see, this is less than one-tenth of the amount we estimate is required as dust. Budyko goes on to point out that the amount of sulfur required to be burnt in the stratosphere to produce the aerosol is 200,000 t, or possibly even as little as 40 percent of this, depending on the amount of water that might be absorbed from the air. Thus the lift requirements might be only one-seventh to one-third of that estimated for sulfuric acid itself. He also assumes 2 years as the lifetime of the aerosol in the stratosphere. In any case, Budyko's maximum requirement is much less than we use below to estimate the cost of the material and lift requirements. (Sulfur costs are about \$0.05/pound, and we assume less than \$0.25/pound for dust.) The costs to do the screening using sulfuric acid aerosol in the stratosphere would be less than those which are estimated below for dust, if we use the estimates of Budyko.

The amount of dust emitted into the atmosphere from natural and man-made (mostly natural) sources is noted (from material quoted by Toon and Pollack, 1976) to be about 1 to 3 Gt/yr, or $1 \text{ to } 3 \times 10^{12} \text{ kg/yr}$.⁸ This is about 100 to 300 times the amount proposed below to be added to the atmosphere.

Mass Estimates

Ramaswamy and Kiehl (1985) estimate that an aerosol dust loading of 0.2 g/m^2 for dust with a radius of about $0.26 \text{ }\mu\text{m}$ increases the planetary albedo by 12 percent, resulting in a 15 percent decrease of solar flux reaching the surface. Since an approximately 1 percent change in solar flux is required, and their Figures 13 and 15 suggest that, at these loadings, the dust effects may reasonably be extrapolated downward linearly, estimates will be made by using a dust loading of 0.02 g/m^2 with a particle radius of $0.26 \text{ }\mu\text{m}$.

Ramaswamy (private communication) points out that their model does not contain clouds. At high loadings of dust, this probably is not too important because the optical thickness of the dust is high. When extrapolating downward in loading by an order of magnitude, the increased albedo due to clouds could be important. A factor of 2 might possibly be used, but careful computations should be done. It seems clear that the required density of dust is distinctly lower than the 0.2 g/m^2 in Ramaswamy and Kiehl's computation, which produces a decrease of 15 percent in radiative forcing. The required loading may be somewhat greater than the 0.02 g/m^2 used below to obtain a 1 percent change in radiative forcing. This effect can presumably be studied by using global climate models. This will broaden the uncertainty band of the system costs, but it seems likely that the costs are between the minimum computed by the panel and 10 times that minimum.

By using 0.02 g/m^2 , the mass of dust required to mitigate 1000 Gt C (4000 Gt CO_2) is 10^{10} kg . Thus a kilogram of dust in the stratosphere mitigates the greenhouse effect of about 100 t C in the atmosphere as CO_2 .⁹ To mitigate the 1989 U.S. input of CO_2 -equivalent greenhouse gases ($8 \times 10^9 \text{ t}$), $2 \times 10^7 \text{ kg}$ of dust would be required.¹⁰

The dust in Ramaswamy and Kiehl's model is distributed between 10 and 30 km in the stratosphere, uniformly over the globe. The actual effect on radiative forcing of a global distribution of additional dust would be somewhat greater at low than at high latitudes because more of the sunlight is effective there for geometric reasons. This would decrease slightly the equator-to-pole temperature gradients and might have some effect on weather intensity. Presumably, this effect can also be studied with global climate models.

Possible Side Effects

This dust heats the stratosphere, and the effect of such heating is included in the computation of Ramaswamy and Kiehl (1985). One possible effect of this heating might be to change the atmospheric chemistry to augment or destroy stratospheric ozone. Additional stratospheric dust could provide additional surface area on which chlorine compounds could be adsorbed, thus possibly increasing the rate of destruction of stratospheric ozone. In the antarctic stratosphere during the winter darkness, chemical reactions involving chlorine compounds derived from the breakup of CFCs take place on the surfaces of ice crystals. These reactions, which do not occur without the presence of the surfaces, produce other chlorine compounds, which, when released and photolyzed (broken up by the action of light) by spring and summer sunshine, produce chemical species that destroy ozone.

Laboratory experiments at stratospheric temperatures appear to show that

similar reactions occur on the surface of sulfuric acid solutions (and presumably would occur on the surfaces of sulfuric acid and dust particles), but are 100 to 1000 times slower (Tolbert et al., 1988). Given the rapid alternation of light and dark at mid-latitudes compared to the 6-month cycling at the poles, these reactions are estimated to account for a ≤ 1 percent depletion of ozone at present. However, in the presence of enhanced concentrations of sulfuric acid (or, presumably, dust) in the stratosphere, the reactions could become much more important.

The El Chichon volcanic eruption in 1982 is estimated to have released 1.2×10^{10} kg of sulfur compounds, compared to the release of 10^{10} kg of dust or aerosol discussed above, leading to a concentration of 0.03 g/m^2 , compared to the target of 0.02 g/m^2 discussed above, about 10 times the background concentration of 0.002 g/m^2 . After this eruption the ozone concentration within the eruption plume in the stratosphere decreased by amounts up to 20 percent. However, since the volcano also emitted enormous quantities of hydrochloric acid (HCl) (equivalent to 9 percent of the existing HCl in the entire stratosphere), it is not clear how much of the depletion was caused by reactions involving the dust and aerosol, and how much was due to the increased Cl from the HCl (Hoffman and Solomon, 1989).

It appears that destruction of stratospheric ozone due to chemical reactions on the surface of added dust or aerosol in the stratosphere is a possible side effect that must be considered and understood before this possible mitigation option can be considered for use.

A National Research Council (1985) report cites papers by Cadle et al. (1976) and Mossop (1963, 1965) that give the amount of silicate particles from the 1963 Mount Agung eruption with sizes between 0.2 and $2.0 \text{ }\mu\text{m}$ as 1×10^{10} kg, about the loading the panel assumed would have to be added. The half-life of this dust is not given, but the life of a sulfate aerosol with a size of 0.2 to $0.45 \text{ }\mu\text{m}$ and a column height of 23 km is given as roughly 1 year, consonant with the panel's lower estimate.

Note that the dust can be expected to produce visible optical effects, such as spectacular sunsets, as in the case of volcanic dust.

Delivery Scenarios

Naval Rifles A 16-inch naval rifle fired vertically could put a shell weighing about 1 t up to an altitude of 20 km . With larger propellant loadings, some sacrifice in payload, or the use of sabots (a device fixed to the shell so that it will fit properly in the rifle barrel), higher altitudes could be achieved. Note that any launch technology could be used, but so much less is known about items such as rail guns that system and cost estimates based on existing launch technologies seemed the best choice.

The economics of keeping 10^{10} kg of dust in the stratosphere is determined by the lifetime of the dust aloft and the means used to put the material there. A dust lifetime in the stratosphere of 2 years is assumed, requiring that 10^{10} kg be placed in the stratosphere 20 times during the 40 years until 2030.

The panel has estimated the cost of such a naval rifle system, and some details of the estimates follow. Full details of the cost estimate are contained in Appendix Q.¹¹

The project is designed to mitigate 10^{12} t C continuously, equivalent to 4×10^{12} t CO₂; the undiscounted 40-year cost is \$5/t C or \approx \$1/t CO₂ mitigated. The undiscounted annual cost is \$0.125/t C/yr, or \$0.03/t CO₂/yr. If a 1-year lifetime is assumed (Hunten's (1975) estimate for the 20-km altitude is 1.25 years), the annual cost will double to \$0.25/t C/yr, or \$0.06/t CO₂/yr. If the amount of dust required is 10 times the amount used for the estimate, the cost might be as high as \$3/t C/yr, or \$0.75/t CO₂/yr. If the quantity to be mitigated is the amount of the 1989 U.S. emissions, the scale of the project can be divided by 500, to give an annual cost of about \$0.25 billion to \$0.50 billion.¹²

To summarize this naval rifle scenario, the system lifts dust to the stratosphere at a rounded cost of about \$10 to \$30/kg of dust. Each kilogram of dust in the stratosphere mitigates about 100 t C. The system mitigates carbon at an undiscounted rounded cost of \$0.1 to \$0.3/t C or \$0.03 to \$0.06/t CO₂. Uncertainty regarding clouds and the required dust density for a 1 percent effect on radiative forcing suggests that it is reasonable, and even conservative, to put these costs in the range \$0.03 to \$1.0/t CO₂ mitigated.

Rockets At the present time, the cost of sounding rocket launches (using available surplus rockets such as the Nike Orion, which cost about \$25,000 and carry a payload of 500 pounds) is about \$100/kg of dust lifted, 5 times the estimated cost of firing the material aloft with large guns. These figures are for launches to 70 km; thus the achievable efficiency should be higher, and costs for a new rocket system might be closer to those estimated for guns.

Balloons Current scientific payload helium balloons lift about 5000 pounds at a cost of \$200,000 per flight, giving a cost of \$80/kg of dust lifted, or about 4 times the cost with naval rifles. Hydrogen balloons might be cheaper. The cost of lifting the dust with hydrogen balloons is estimated in Appendix Q and appears to be in the same range as that estimated for 16-inch naval rifles. Hot-air balloons do not appear to be as cost-effective as hydrogen balloons. The design and cost of such balloons are also discussed in detail in Appendix Q.¹³

Aircraft Exhaust Penner et al. (1984) suggested that emissions of 1 percent of the fuel mass of the commercial aviation fleet as particulates, between 40,000- and 100,000-foot (12- to 30-km) altitude for a 10-year period, would change the planetary albedo sufficiently to neutralize the effects of an equivalent doubling of CO_2 . They proposed that retuning the engine combustion systems to burn rich during the high-altitude portion of commercial flights could be done with negligible efficiency loss. Using Reck's estimates of extinction coefficients for particulates (Reck, 1979a, 1984), they estimated a requirement of about 1.168×10^{10} kg of particulates, compared with the panel's estimate of 10^{10} kg, based upon Ramaswamy and Kiehl (1985). They then estimated that if 1 percent of the fuel of aircraft flying above 30,000 feet is emitted as soot, over a 10-year period the required mass of particulate material would be emitted.

However, current commercial aircraft fleets seldom operate above 40,000 feet (12 km), and the lifetimes of particles at the operating altitudes will be much shorter than 10 years. An estimate (National Research Council, 1985) for the half-life of smoke is 1.4×10^{-7} s.¹⁴ This gives a half-life of 83 days, or a little less than one-quarter of a year. Thus the amount of fuel to be turned into soot continuously for complete mitigation (10^{12} t C) is closer to 40 percent than to 1 percent. That seems impractical. However, if the amount of mitigation required is equivalent to the 1989 U.S. emissions of greenhouse gases equivalent to CO_2 (8×10^9 t CO_2), the amount of soot required would be 500 times smaller, and the required soot corresponds to less than 0.1 percent of the fuel burned. If 1 percent of the fuel were used, about 25×10^9 t CO_2 /yr could be mitigated.

In 1987, 16 percent of the cash operating expenses of airlines were spent on fuel (U.S. Bureau of the Census, 1988). Because the operating revenue in that year was \$45,339 million, the approximate cost of the particulate emissions from jet engines for mitigation of the 1989 U.S. CO_2 equivalent emissions would be about \$7 million, or about \$0.001/t CO_2 /yr plus the capital costs of adjusting the aircraft engines.

This provides a cost range of \$0.001 to \$0.1/t CO_2 /yr. An alternate possibility is simply to lease commercial aircraft to carry dust to their maximum flight altitude, where they would distribute it. To make a cost estimate, a simple assumption is made that the same amount of dust assumed above for the stratosphere would work for the tropopause (the boundary between the troposphere and the stratosphere). The results can be scaled for other amounts. The comments made above about the possible effect of dust on stratospheric ozone apply as well to ozone in the low stratosphere, but not in the troposphere. The altitude of the tropopause varies with latitude and season of the year.

In 1987, domestic airlines flew 4,339 million ton-miles of freight and express, for a total express and freight operating revenue of \$4,904 million

(U.S. Bureau of the Census, 1988). This gives a cost of slightly more than \$1 per ton-mile for freight. If a dust distribution mission requires the equivalent of a 500-mile flight (about 1.5 hours), the delivery cost for dust is \$500/t, and ignoring the difference between English and metric tons, a cost of \$0.50/kg of dust. If 10^{10} kg must be delivered each 83 days, (provided dust falls out at the same rate as soot), 5 times more than the 1987 total ton-miles will be required. The question of whether dedicated aircraft could fly longer distances at the same effective rate should be investigated. However, if the requirement is to mitigate the 1989 U.S. emissions of CO_2 , 500 times less dust is needed, the cost is about \$10 million per year, and implementation would require about 1 percent of the ton-miles flown in 1987. If 10 percent of the ton-miles flown in 1987 were used, the system could mitigate 80 Gt CO_2 . These costs should probably be increased by the cost of delivered dust (say, \$0.50/kg) and of delivery systems in the aircraft, but better-than-average freight rates could probably be arranged. Thus the costs appear to be about \$0.0025/t CO_2 .

Clearly, the amount of dust required could be greater by a factor of 10, and the cost would be \$0.025/t CO_2 . This provides a cost estimate in the range of \$0.003 to \$0.03/t CO_2 .

Multiple Balloon Screen

A screen can be created by putting a vast number of aluminized, hydrogen-filled balloons at a high enough altitude that they do not interfere with air traffic. They would provide a reflection screen. The properties of such a system are examined in Appendix Q.

The multiple balloon parasol system requiring billions of 1- to 6-m-diameter balloons would appear to cost about 20 times as much as distributing dust in the stratosphere. The large number of balloons, and the trash problem posed by their fall, make the system somewhat unattractive.

Changing Cloud Abundance

A more detailed discussion of the possibility of changing cloud abundance appears as Appendix Q.

The Approach

Independent studies estimated that an approximately 4 percent increase in the coverage of marine stratocumulus clouds would be sufficient to offset CO_2 doubling (Reck, 1978; Randall et al., 1984). Albrecht (1989) suggests that the average low-cloud reflectivity could be increased if the abundance of cloud condensation nuclei (CCN) increased due to emissions of SO_2 . It

is proposed that CCN emissions should be released over the oceans, that the release should produce an increase in the stratocumulus cloud albedo only, and that the clouds should remain at the same latitudes over the ocean where the surface albedo is relatively constant and small.

Albrecht (1989) estimates that a roughly 30 percent increase in CCN would be necessary to increase the fractional cloudiness or albedo of marine stratocumulus clouds by 4 percent. Albrecht's idealized stratocumulus cloud, which he argues is typical, has a thickness of 375 m, a drizzle rate of 1 mm per day, and a mean droplet radius of 100 μm , and he assumes that each droplet is formed by the coalescence of 1000 smaller droplets. The rate at which the CCN are depleted by his model is 1000/cm³ per day. Consequently, about 300/cm³ per day (30 percent of 1000) of additional CCN would have to be discharged per day at the base of the cloud to maintain a 4 percent increase in cloudiness. This assumes that the perturbed atmosphere would also remain sufficiently close to saturation in the vicinity of the CCN that additional cloud cover would be formed every time the number of CCN increased.

Mass Estimates of Cloud Condensation Nuclei

With Albrecht's assumption in mind that cloudiness in a typical ocean region is limited by the small number of CCN, we now extrapolate to the entire globe. On the average, 31.2 percent of the globe is covered by marine stratiform clouds (Charlson et al., 1987). If no high-level clouds are present, the number n of CCN that need to be added per day is 1.8×10^{25} CCN/day. The mass of a CCN is equal to $4/3\pi r^3 \times \text{density}$, and it is assumed that the mean radius r is equal to 0.07×10^{-4} cm (Charlson et al., 1987). Because the density of sulfuric acid (H_2SO_4) is 1.841 g/cm³, the CCN mass is 2.7×10^{-15} g. The total weight of H_2SO_4 to be added per day is 31×10^3 t per day SO_2 if all SO_2 is converted to H_2SO_4 CCN.

To put this number in perspective, a medium-sized coal-fired U.S. power plant emits about this much SO_2 in a year. Consequently, the equivalent emissions of 365 U.S. coal-burning power plants, distributed homogeneously, would be needed to produce sufficient CCN.

To estimate the value of the sulfur directly, the total weight of SO_2 to be added per day would equal 32×10^3 t, or about 16×10^3 t of sulfur (S) per day, which is equivalent to about 6×10^6 t S/yr. If the average market price of sulfur delivered at the mine or plant is taken as \$96.60/t for the years 1983 to 1987, the cost would be about \$580 million per year. Equating this yearly cost to the 300 parts per million by volume (ppmv) of CO_2 necessary for full compensation gives $\$580 \times 10^6/\text{yr}/(3890 \times 10^6 \text{ t C/ppmv } \text{CO}_2 \times 300 \text{ ppmv } \text{CO}_2)$, or about a fraction of 1 cent/t CO_2 . To obtain an equivalence to conserved carbon, known emissions of carbon in 1978, 1979, and 1980

have been compared with the total measured increase of CO_2 to obtain the equivalence: $3890 \times 10^6 \text{ t C} \equiv 1 \text{ ppmv CO}_2$. A 4 percent increase in cloudiness was then equated to a 300-ppmv CO_2 decrease, which translates into a reduction of 1200 Gt C or 4400 Gt CO_2 .

Cost Estimates

The primary cost of this process involves the mechanism for distributing SO_2 in the atmosphere at the correct location. Assume a fleet of ships, each carrying sulfur and a suitable incinerator. The ships are dedicated to roaming the subtropical Pacific and Atlantic oceans far upwind of land while they burn sulfur. They are vectored on paths to cloud-covered areas by a control center that uses weather satellite data to plan the campaign. In addition to choosing areas that contain clouds, it would be important to distribute the ships and their burning pattern so as not to create major regional changes, or the kind of change with a time or space pattern likely to force unwanted wave patterns. These restrictions (which perhaps cannot now be defined) could present a difficult problem for such a system to solve.

From the above, $16 \times 10^3 \text{ t}$ per day or $6 \times 10^6 \text{ t/yr}$ would be needed. If we allocate 10^2 t per ship per day, and a ship stays out 300 days each year, roughly 200 ships of 10,000-t capacity (one reprovisioning stop every 100 days) are required. At a cost of \$100 million per ship (surely generous), the capital cost of the fleet is \$20 billion. Amortized over 20 years, the annual capital cost is \$1 billion. Sulfur will cost another \$0.6 billion per year, and \$2 million per ship per year for operating costs (this is \$10,000 per operating day), giving a total cost of \$2 billion per year. Over 40 years (until 2030), this gives a cost of \$80 billion, or approximately \$100 billion. This continuously mitigates 10^3 Gt , for a cost of \$0.10/t C/yr, or \$0.025/t CO_2 /yr. This provides a cost estimate in the range of \$0.03 to \$1/t CO_2 . Of course, this continues to be a yearly cost of \$2 billion per year.

The SO_2 could also be emitted from power plants. These plants could be built out in the ocean near the equator (the Pacific gives more room than the Atlantic) and could furnish power for nearby locations (e.g., South America). Transmission or use of the power in the form of refined materials, or possibly by the use of superconducting power transmission systems, could be considered. It would likely require eight large power plants using "spiked" coal (with 4 times the normal amount of sulfur), at a cost of \$2 to \$2.5 billion per plant. Most of the cost might be borne by those buying the power; so imagining a cost of, at most, 10 percent per year (the interest on the investment), total cost would be \$2 billion per year (with the above conversion, $\$2 \times 10^9 / 3890 \times 10^6 \times 300 \approx \$0.0005/\text{t CO}_2$).

Possible Acid Deposition

One must consider whether the injection of this much additional SO_2 into the atmosphere would cause an acid deposition problem. It must be kept in mind that the principal component of naturally occurring CCN is sulfate from marine algae. Schwartz (1988) quotes estimates of 16 to 40×10^{12} g/yr or perhaps about 25×10^9 kg/yr emitted from this source. The addition of about 6×10^9 kg/yr, one-quarter of the total natural amount, is being considered, although locally much more would be added to the amount naturally present. The oceans have an enormous buffering capacity (Stumm and Morgan, 1970), so that the additional rainout of sulfate (especially after dilution through cloud dispersal and droplet coalescence) seems unlikely to have any effect, even locally, although there is clear disagreement on this point. The principal concern would be to avoid additional sulfate deposition over land. With a 30 percent rainout per day, this could be ensured to a 90 percent level by operating about a week upwind of land. Such a constraint would have to be added to the others stated above.

Another possible way of dealing with the problem of acid rain would be to introduce sulfate in the form of ammonium sulfate or bisulfate, both of which are neutral salts. This would avoid the acid question from the start. These salts are frequently used as fertilizers and, in the dilutions to be seen here, would have a mild fertilizing effect locally. These salts can be made by reacting ammonia with sulfuric acid. The price of ammonia is about \$100/t, so the cost of the CCN might double, and there would be an additional cost for equipment to run the reaction at sea. These additional costs might increase the total by as much as 50 percent, to \$0.15/t C mitigated per year or \$0.04/t CO_2 .

It may also be sensible to consider using ships that pump a seawater aerosol into the air above the ocean, thus increasing the density of sea salt aerosol crystals, which can act as CCN (Latham and Smith, 1990).

ATMOSPHERIC CHLOROFLUOROCARBON REMOVAL

Another option for mitigating greenhouse warming could be to remove chlorofluorocarbons (CFCs) from their principal reservoir, the lower atmosphere or troposphere. The expected tropospheric residence time for CFCs exceeds 65 years (cf. Table 19.2); evidently these highly inert gases disappear only by very slow loss to the stratosphere, where ultraviolet rays from the sun cause molecular decomposition. A reasonable query is whether this natural process of CFC depletion can be significantly enhanced by large-scale technical means.

It has been suggested that extremely powerful lasers might be used to break up tropospheric CFCs (Stix, 1989). Vast arrays of pulsed lasers at

mountain altitudes would launch intense infrared beams into the atmosphere. The laser beams would then selectively destroy chlorofluorocarbon molecules in the atmosphere through the process of multiphoton dissociation. Due to the low atmospheric concentration of the CFCs (less than one part per billion by volume), any process to remove them must be highly selective. That is, the process cannot afford to waste energy in reactions involving any of the far more abundant non-CFC molecules in the atmosphere. The suggested laser scheme then depends first upon finding bands of strong laser-light absorption by CFC molecules. Second, within these bands, one must find "spectral windows" where absorption of the laser light by non-CFC molecules in the atmosphere is virtually absent. Computer calculations making use of an extensive atmospheric-gas infrared cross-section data base suggest that 90 percent transmission over 50-km paths would be possible through dry atmospheres.

Nevertheless, a large number of questions remain unexplored, among them laser and optical technology, electro-optical conversion efficiency, anomalous or unexpected laser-light absorption channels including excited-state processes and stimulated rotational Raman scattering, infrared band-pass mirrors, adequate laser selectivity, pulse shaping benefits, wind velocity and atmospheric humidity patterns, site availabilities, and safety and ecology. Even making very optimistic assumptions about the resolution of these and other questions, the expense associated with the installation and operation of the elaborate and extensive laser facilities would be prohibitive: to remove 10 percent of the atmospheric CFCs per year, the electric power bill alone is estimated to exceed \$10 billion. Nevertheless, if technological breakthroughs were to introduce a factor of 10 to 20 improvement in overall efficiency, the cost of such processing of the atmosphere, although very large indeed, might be worth evaluating.

In conclusion, the panel does not believe that the use of lasers to remove CFCs from the atmosphere is currently feasible.

CONCLUSIONS

Several of the geoengineering possibilities discussed in this chapter, including atmospheric CFC removal, space mirrors, and the multiple balloon stratospheric screen, appear, with current technology or that expected to be available soon, to be either impractical, too cumbersome to manage, or too expensive. These ideas might merit some further study to be certain of this conclusion but do not now seem worth great effort. They should be kept in mind, however, because technological changes may make them more attractive.

Reforestation is a low-cost, ecologically attractive option that could be adopted rapidly as an expanded program. It is, however, limited in its low-

cost form by the easy availability of appropriate land. Therefore the panel hesitates to look beyond its initial potential mitigation of 240 Mt CO₂/yr. In addition, a number of years would be required to build reforestation to its full mitigation potential.

Stimulation of ocean biomass with iron may be feasible and would be a relatively low-cost option. Its application appears to be limited at most to the mitigation of about 7 Gt CO₂ equivalent per year (about 1.5 times U.S. annual CO₂ emissions). The biological, ecological, and ocean chemical and physical dynamics of this possibility are not well understood and should be investigated further, both theoretically and experimentally. There continue to be questions as to whether iron is the limiting nutrient. Furthermore, the circulation dynamics of the antarctic ocean might severely limit the effect. If feasible, the mitigation potential of the possibility—storage of CO₂ in a standing crop and as dissolved CO₂ with slow sequestering of carbon to the ocean bottom—could probably be established over several years. If applications of iron were stopped, the standing crop would be expected to die within days or weeks, thus ending the mitigation effect.

Cloud stimulation by provision of cloud condensation nuclei appears to be a feasible and low-cost option capable of being used to mitigate any quantity of CO₂ equivalent per year. Details of the cloud physics, verification of the amount of CCN to be added for a particular degree of mitigation, and the possible acid rain or other effects of adding CCN over the oceans need to be investigated before such a system is put to use. Once a decision has been made, the system could be mobilized and begin to operate in a year or so, and mitigation effects would be immediate. If the system were stopped, the mitigation effect would presumably cease very rapidly, within days or weeks, as extra CCN were removed by rain and drizzle.

Several schemes depend on the effect of additional dust (or possibly soot) in the stratosphere or very low stratosphere screening out sunlight. Such dust might be delivered to the stratosphere by various means, including being fired with large rifles or rockets or being lifted by hydrogen or hot-air balloons. These possibilities appear feasible, economical, and capable of mitigating the effect of as much CO₂ equivalent per year as we care to pay for. (Lifting dust, or soot, to the tropopause or the low stratosphere with aircraft may be limited, at low cost, to the mitigation of 8 to 80 Gt CO₂ equivalent per year.) Such systems could probably be put into full effect within a year or two of a decision to do so, and mitigation effects would begin immediately. Because dust falls out naturally, if the delivery of dust were stopped, mitigation effects would cease within about 6 months for dust (or soot) delivered to the tropopause and within a couple of years for dust delivered to the midstratosphere.

Such dust would have a visible effect, particularly on sunsets and sunrises, and would heat the stratosphere at the altitude of the dust. The

heating would have an effect on the chemistry of the stratospheric ozone layer, and this possibility must be considered before major use of such a mitigation system. The amount of dust to be added is within the range of that added from time to time by volcanic eruption, so the effects on climate would not be expected to go beyond those experienced naturally. However, either the natural or the artificial effects on the chemistry might be very serious under conditions of increased CFC chlorine in the stratosphere, and the result of having these effects continuously must be considered, so the option might not be usable. Better specification of dust characteristics and size for best effect and better data on the fallout rate of dust from various altitudes as well as on chlorine chemistry are needed. It will be important to observe the effects on stratospheric chemistry of any volcanic eruptions that occur, with special attention to separating the effects of dust, aerosol, and hydrochloric acid.

Of these systems to alter the planetary albedo, the increase of low-level marine clouds by increasing CCN and the delivery of dust to the stratosphere by using large rifles seem the most promising. The rifle system appears to be inexpensive, to be relatively easily managed, and to require few launch sites. However, the possible effect of the additional stratospheric dust on ozone chemistry may be a serious problem, and the noise of the rifles would have to be managed. Balloons also appear to be a good possibility, but the return of the balloons to ground level would require management.

Sunlight screening systems would not have to be put into practice until shortly before they were needed for mitigation, although research to understand their effects, as well as design and engineering work, should be done now so that it will be known whether these technologies are available if wanted.

Perhaps one of the surprises of this analysis is the relatively low costs at which some of the geoengineering options might be implemented. If, however, further analyses support the preliminary conclusions, it will bear further inquiry to decide if they can produce the targeted responses without unacceptable additional effects. The level at which we are currently able to evaluate the cost-effectiveness of engineering the global mean radiation balance leaves great uncertainty in both technical feasibility and environmental consequences. This analysis does suggest that further inquiry is appropriate.

NOTES

1. Throughout this report, tons (t) are metric; 1 Mt = 1 megaton = 1 million tons; 1 Gt = 1 gigaton = 1 billion tons.

2. The ships can distribute material across the lane by towing hoses spread away from the ship with paravanes, a well-known minesweeping technology.

3. $4\pi(6.6)^2 \times 10^6 \text{ km}^2 \times (10^3 \text{ m/km})^2 = 547 \times 10^{12} \text{ m}^2 \cong 5 \times 10^{14} \text{ m}^2$. The screening only requires covering the illuminated disk, or πr^2 , but in many of the cases treated it will not be possible to maneuver the screening material so as to remain only above the sunlit side of the disk, therefore $4\pi r^2$ is used.

4. The correct parasol coverage area may be 1.4 percent because the Ramanathan computation is for 1 percent increase in the 30 percent albedo, but this change will have slight effect on the estimates. See also Penner et al. (1984), who estimate a dust requirement of $1.168 \times 10^{10} \text{ kg}$.

5. The current space transportation system costs about \$5200/kg; \$130 million per launch with a capacity of 55,000 pounds to 160 nautical miles at 28.5 degrees. A Delta rocket costs \$45 million per launch for 11,000 pounds to 100 nautical miles, or \$9000/kg. Even at \$100/kg, the cost of the material would be only 2 percent of the cost of putting the material into orbit.

6. If the correct equivalence is 1 percent to 1200 Gt, for example, all material quantities, etc., are smaller by a factor of 10/12; if the equivalence is 800 Gt, the numbers are larger by a factor of 10/8, etc. For costs per ton of CO_2 , all costs per ton of carbon should be divided by $44/12 \cong 4$.

7. In this connection, see also Early (1989). Estimates range between \$1/t CO_2 /yr for the lower launch cost and long-lived mirrors and \$10/t CO_2 /yr for the higher cost and annual replenishment.

8. From Toon and Pollack (1976), one can make a crude estimate of the mass of lower stratospheric dust by noting that they give the density at 20 km as about 1 mg/m³. The "all sizes" curve in their Figure 9 suggests a reasonably constant concentration in the 8 km from 12 to 20 km. So the mass can be taken to be roughly $5 \times 10^{14} \text{ m}^2 \times 8 \times 10^3 \text{ m} \times 10^{-6} \text{ g/m}^3 = 40 \times 10^{11} \text{ g} = 4 \times 10^{12} \text{ g} = 4 \times 10^9 \text{ kg}$, or roughly half the amount to be injected to form the screen.

9. It is interesting that this is the same mass as that computed above for the space mirror, given an assumed density of 2 g/cm³ for dust instead of the 1 g/cm³ used previously (clay has a density of 1.8 to 2.6, alumina of 4, basaltic lava of 2.8 to 3.0).

10. Another suggestion is to shape the dust into highly conductive needles about 0.1 m in radius by 0.5 m long, the scattering at an optical wavelength of 1 m would be dipole scattering with an effective scattering cross section 100 times greater than for spheres, thus requiring 100 times less material. Mack and Reiffen (1964) computed these effects in connection with the West Ford project. The maximum cross section expected for a perfectly conducting half-wave resonant dipole is 0.86λ . In the case of a dipole such as that specified above, which has an area of $1/2 \times 1/5 \lambda$ a scattering cross section enhancement of $0.86 \times 10 = 8.6$ is obtained. This enhancement would be decreased by averaging over all angles of the dipole to the incoming radiation. Mack and Reiffen compute this effect to be about 0.1 for backscattering for several polarizations of the incoming light. In addition, highly conducting dipoles would have Q values too large to cover the necessary optical bandwidth effectively. It appears that assuming Mie scattering of dust with a size spectrum optimized to the scattering of the visible part of the solar spectrum, roughly comparable to the estimate of Ramaswamy and Kiehl (1985), is fairly efficient.

11. Material from staff at Naval Surface Weapons Center, Dahlgren, Virginia, was furnished to John I. Connally, Jr., vice president of Scientific Applications

International Corporation, and by him in a letter to Lee Hunt, executive director, Naval Studies Board, National Research Council.

12. The cost factors will scale proportionately except for any economies of scale, which have not been considered.

13. Data for Nike Orion and scientific balloons from Ray Pless (Wallops Island, NASA, private communication, 1990).

14. This estimate uses the value given in Table 7.2 of National Research Council (1985) for the column (Turco et al., 1983) at 11 to 13 km.

REFERENCES

- Albrecht, B. A. 1989. Aerosols, cloud microphysics, and fractional cloudiness. *Science* 245:1227-1230.
- Barnola, J. M., D. Raynaud, Y. S. Korotkevich, and C. Lorius. 1987. Vostock ice core provides 160,000 year record of atmospheric CO₂. *Nature* 329:408-414.
- Budyko, M. I. 1982. *The Earth's Climate: Past and Future*. New York: Academic Press.
- Cadle, R. D., C. S. Kiang, and J-F. Louis. 1976. The global scale dispersion of the eruption clouds from major volcanic eruptions. *Journal of Geophysical Research* 81(18):3125-3132.
- Charlson, R. J., J. E. Lovelock, M. O. Andreae, and S. G. Warren. 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature* 326:655-661.
- Chemical Marketing Reporter. 1991. Chemical prices for week ending March 29, 1991. (April 11):35.
- De Baar, H. J. W., A. G. J. Buma, R. F. Nolting, G. C. Cadee, G. Jacques, and P. J. Treguer. 1990. On iron limitations of the southern ocean: Experimental observations in the Weddell and Scotia seas. *Marine Ecology Progress Series* 65:105-122.
- Early, J. T. 1989. Space-based solar shield to offset greenhouse effect. *Journal of the British Interplanetary Society* 42:567-569.
- Heilman, P. E., and R. F. Stettler. 1985. Genetic variation and productivity of *Populus Trichocarpa* T and G and its hybrids. II. Biomass production in a 4-year plantation. *Canadian Journal of Forest Research* 15:384-388.
- Hoffman, D. J., and S. Solomon. 1989. Ozone destruction through heterogeneous chemistry following the eruption of El Chichon. *Journal of Geophysical Research* D4 94:5029-5041.
- Hunten, D. M. 1975. Residence times of aerosols and gases in the stratosphere. *Geophysical Research Letters* 2(1):26-27.
- Kellogg, W. W., and S. H. Schneider. 1974. Climate stabilization: For better worse? *Science* 186:1163-1172.
- Knox, F., and M. B. McElroy. 1984. Changes in atmospheric CO₂: Influence of the marine biota at high latitude. *Journal of Geophysical Research* 89:4629-4637.
- Latham, J., and M. H. Smith. 1990. Effect on global warming of wind-dependent aerosol generation at the ocean surface. *Nature* 347:372-373.

- Mack, C. L., Jr., and B. Reiffen. 1964. RF characteristics of thin dipoles. *Proceedings of the IEEE* 52:533-542.
- Marland, G. 1988. The Prospect of Solving the CO₂ Problem Through Global Reforestation. Report DOE/NBB-0082. Oak Ridge, Tenn.: Oak Ridge National Laboratory.
- Martin, J. H. 1990. Glacial-interglacial CO₂ change: The iron hypothesis. *Paleoceanography* 5:1-13.
- Martin, J. H., and S. E. Fitzwater. 1988. Iron deficiency limits phytoplankton growth in the northeast Pacific subarctic. *Nature* 331:341-343.
- Martin, J. H., and R. M. Gordon. 1988. Northeast Pacific iron distribution in relation to phytoplankton productivity. *Deep-Sea Research* 35:177-196.
- Martin, J. H., R. M. Gordon, and S. E. Fitzwater. 1990. Iron in antarctic waters. *Nature* 345:156-159.
- Mossop, S. C. 1963. Stratospheric particles at 20 km. *Nature* 199:325-326.
- Mossop, S. C. 1965. Stratospheric particles at 20 km altitude. *Geochimica et Cosmochimica Acta* 29:201-207.
- Moulton, R. J., and K. R. Richards. 1990. Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States. General Technical Report WO-58. Washington, D.C.: Forest Service, U.S. Department of Agriculture.
- Mueller, A. C., and D. J. Kessler. 1985. The effects of particulates from solid rocket motors fired in space. *Advances in Space Research* 5(2):77-86.
- National Research Council. 1985. The Effects on the Atmosphere of a Major Nuclear Exchange. Washington, D.C.: National Academy Press.
- National Research Council. 1990. Forestry Research: A Mandate for Change. Washington, D.C.: National Academy Press.
- Neftel, A., H. Oeschger, J. Schwander, B. Stauffer, and R. Zimbrunn. 1982. Ice core sample measurements give atmospheric CO₂ content during the past 40,000 yrs. *Nature* 295:220-223.
- Oeschger, H., U. Siegenthaler, U. Schatterer, and A. Gugelmann. 1975. Box diffusion-model to study carbon dioxide exchange in nature. *Tellus* 27:168-192.
- Peale, S. J. 1966. Dust belt of the earth. *Journal of Geophysical Research* 71(3):911-932.
- Peng, T. H., and W. S. Broecker. 1991. Dynamical limitations on the antarctic iron fertilization strategy. *Nature* 349:227-229.
- Penner, S. S., A. M. Schneider, and E. M. Kennedy. 1984. Active measures for reducing the global climatic impacts of escalating CO₂ concentrations. *Acta Astronautica* 11(6):345-348.
- Ramanathan, V. 1988. The greenhouse theory of climate change: A test by an inadvertent experiment. *Science* 243:293-299.
- Ramaswamy, V., and J. T. Kiehl. 1985. Sensitivities of the radiative forcing due to large loadings of smoke and dust aerosols. *Journal of Geophysical Research* 90(D3):5597-5613.
- Randall, D. A., J. A. Coakley, Jr., C. W. Fairall, R. A. Kropfli, and D. H. Lenschow. 1984. Outlook for research on subtropical marine stratiform clouds. *American Meteorological Society Bulletin* 65(12):1290-1301.

- Reck, R. A. 1978. Thermal Effects of Cloud Parameter Variations in the Manabe-Wetherald Radiative-Convective Atmospheric Model. Report GMR-2820. Warren, Mich.: General Motors Research Laboratories, and paper presented at the Conference on the Parameterization of Extended Clouds and Radiation for Climate Models, sponsored by the International Council of Scientific Unions and organized by the Joint Organizing Council of the Global Atmospheric Research Program of the United Nations, Oxford, England, September 1978.
- Reck, R. A. 1979a. Comparison of fixed cloud-top temperature and fixed cloud-top altitude approximations in the Manabe-Wetherald radiative-convective atmospheric model. *Tellus* 31:400-405.
- Reck, R. A. 1979b. Carbon dioxide and climate: Comparison of one- and three-dimensional models. *Environment International* 2:387-391.
- Reck, R. A. 1984. Climatic Impact of Jet Engine Distribution of Alumina (Al_2O_3): Theoretical Evidence for Moderation of Carbon Dioxide (CO_2) Effects. Report GMR-4740. Warren, Mich.: General Motors Research Laboratories, and paper presented to the American Geophysical Union, San Francisco, Calif., December 1984.
- Sarmiento, J., and J. R. Toggweiler. 1984. A new model for the role of the oceans in determining atmospheric pCO_2 . *Nature* 308:621-624.
- Schwartz, S. E. 1988. Are global cloud albedo and climate controlled by marine phytoplankton? *Nature* 336:441-445.
- Siegenthaler, U., and T. Wenk. 1984. Rapid atmospheric CO_2 variations and ocean circulation. *Nature* 308:624-626.
- Steinbeck, K., and C. L. Brown. 1976. Yield and Utilization of Hardwood Fiber Grown on Short Rotations. *Applied Polymer Symposium*, 28:393-401. New York: Wiley & Sons.
- Stix, T. H. 1989. Removal of chlorofluorocarbons from the atmosphere. *Journal of Applied Physics* 66:5622-5626.
- Stumm, W., and J. J. Morgan. 1970. *Aquatic Chemistry*. New York: Wiley-Interscience.
- Tans, P. P., I. Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric carbon dioxide budget. *Science* 247:1431-1438.
- Tolbert, M. A., M. J. Rossi, and D. M. Golden. 1988. Heterogeneous interactions of chlorine nitrate, hydrogen chloride, and nitric acid with sulfuric acid surfaces at stratospheric temperatures. *Geophysical Research Letters* 8(15):847-850.
- Toon, O. B., and J. B. Pollack. 1976. A global average model of atmospheric aerosols for radiative transfer calculations. *Journal of Applied Meteorology* 15:225-246.
- Turco, R. P., O. B. Toon, T. Ackerman, J. B. Pollack, and C. Sagan. 1983. Nuclear winter: Global consequences of multiple nuclear explosions. *Science* 222:1283-1293.
- U.S. Bureau of the Census. 1988. *Statistical Abstract of the United States: 1989*, 109th edition. Washington, D.C.: Government Printing Office.
- U.S. Forest Service. 1990. *FY 1989 U.S. Forest Planting Report*. Washington, D.C.: U.S. Forest Service, U.S. Department of Agriculture.
- World Resources Institute. 1990. *World Resources Report 1990-91*. New York: Oxford University Press.