Page 1

Annu. Rev. Energy Environ. 2000. 25:245–84

GEOENGINEERING THE CLIMATE: History and Prospect [1]

David W. Keith
Department of Enginering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213; e-mail: keith@cmu.edu

Key Words climate change, weather modification, mitigation, earth systems engineering, integrated assessment, environmental history

s **Abstract** **Geoengineering** is the intentional large-scale manipulation of the environment, particularly manipulation that is intended to reduce undesired anthropogenic climate change. The post-war rise of climate and weather modification and the history of U.S. assessments of the CO_2-climate problem is reviewed. Proposals to engineer the climate are shown to be an integral element of this history. Climate engineering is reviewed with an emphasis on recent developments, including low-mass space-based scattering systems for altering the planetary albedo, simulation of the climate's response to albedo modification, and new findings on iron fertilization in oceanic ecosystems. There is a continuum of human responses to the climate problem that vary in resemblance to hard **geoengineering** schemes such as space-based mirrors. The distinction between **geoengineering** and mitigation is therefore fuzzy. A definition is advanced that clarifies the distinction between **geoengineering** and industrial carbon management. Assessment of **geoengineering** is reviewed under various framings including economics, risk, politics, and environmental ethics. Finally, arguments are presented for the importance of explicit debate about the implications of countervailing measures such as **geoengineering**.

CONTENTS

[1] Acronyms used in text: COM, Cost of Mitigation; FAR/SAR/TAR, First/Second/Third Assessment Report of the IPCC; FCCC, Framework Convention on Climate Change; ICM, Industrial Carbon Management; IPCC, Inter-Governmental Panel on Climate Change; MIT, Massachusettes Institute of Technology; NAS, National Academy of Science; NASA, National Aeronautics and Space Administration; NSF, National Science Foundation; WG, Working Group.

1056-3466/00/1129-0245$14.00

1. INTRODUCTION

The possibility of using **geoengineering**—the deliberate manipulation of the planetary environment—to counteract anthropogenic climate change is deeply controversial. At least in name, **geoengineering** has largely been ignored in recent climate assessments (1, 2). Under close examination, however, the distinction between **geoengineering** and other responses to the CO_2-climate problem proves to be fuzzy. Use of the term **geoengineering** is shifting, as advocates of response strategies that were formerly labeled **geoengineering** now seek to avoid the term. Section 2 elaborates a definition of **geoengineering**; assessment of the implications of its shifting meaning are deferred to the concluding discussion.

Historical perspective is vital to understanding the role of **geoengineering** in human choices about climate. The historical background sketched in Section 3 shows that proposals to engineer the climate are deeply woven into the history of shows that proposals to engineer the climate are deeply woven into the history of the CO_2-climate problem. The focus is on the postwar rise of weather and climate modification and the interweaving of its decline with rising concern about inadvertent climate modification. The evolving status of **geoengineering** as a response to anthropogenic climate change is examined through a review of U.S. climate assessments and the IPCC assessment reports.

Section 4 reviews proposals to geoengineer the climate. Structure for the review is provided by a taxonomy of anthropogenic climate modification that includes **geoengineering** to counter anthropogenic climate forcing as a special case. Whereas the structure is broad, treatment of detailed proposals focuses on recent work that was not covered by previous reviews of **geoengineering** (3–7). Recent developments include analysis of very low-mass scattering systems for

---

altering planetary albedo (8), climate model simulation of the effect of albedo **geoengineering** (9), improved scientific understanding of the role of iron as a limiting nutrient in oceanic ecosystems (10, 11), and speculation about the use of genetically modified organisms to enhance carbon sinks (12, 13).

Section 5 surveys frameworks for assessing **geoengineering**; they include economics, risk and uncertainty, politics and law, and environmental ethics. Finally, the concluding section suggests that the fuzziness of the boundary demarcating **geoengineering** from conventional mitigation arises from deep uncertainties about the appropriate extent of deliberate human management of global biogeochemical systems. Although most **geoengineering** methods may reasonably be viewed as marginal to the debate about climate change, the failure of modern assessments to consider their implications has encouraged avoidance of questions about the appropriate extent of deliberate planetary management—questions that warrant serious debate.

2. DEFINING GEOENGINEERING

2.1 Etymology and Definition

In this review **geoengineering** is defined as intentional large-scale manipulation of the environment. Scale and intent play central roles in the definition. For an action to be **geoengineering**, the environmental change must be the primary goal rather than a side effect and the intent and effect of the manipulation must be large in scale, e.g. continental to global. Two examples serve to demonstrate the roles of scale and intent. First, intent without scale: Ornamental gardening is the intentional manipulation of the environment to suit human desires, yet it is not **geoengineering** because neither the intended nor realized effect is large-scale. Second, scale without intent: The modification of global climate owing to increasing atmospheric CO_2 has global effect, yet it is not **geoengineering** because it is a side effect resulting from combustion of fossil fuels with the aim of providing energy services from combustion of fossil fuels with the aim of providing energy services.

Manipulations need not be aimed at changing the environment, but rather may aim to maintain a desired environmental state against perturbations—either natural or anthropogenic. Indeed, the term **geoengineering** has usually been applied to proposals to manipulate the environment with the goal of reducing undesired climate change caused by human influences. The focus of this review is likewise on climatic **geoengineering**, primarily—but not exclusively—to counter CO_2-induced climate change. In this usage, **geoengineering** implies a countervailing measure or a "technical fix." As we will see, the definition of **geoengineering** is ambiguous, and the distinction between **geoengineering** and other responses to climate change is of degree, not of kind. Three core attributes will serve as markers of **geoengineering**: scale, intent, and the degree to which the action is a countervailing measure.

The first use of the term **geoengineering** in approximately the sense defined above was by Marchetti in the early 1970s to describe the mitigation of the climatic impact of fossil fuel combustion by the injection of CO_2 into the deep

ocean (14). The term entered the mainstream of debate about climate change during the past decade, particularly with publication of the 1992 NAS assessment (15).

Geoengineering is not in standard dictionaries. In technical usage it has at least one other not wholly unrelated meaning, as a contraction of geotechnical engineering: the "science that deals with the application of geology to engineering" (16). If the definition outlined above is accepted, a fitting etymology is readily constructed: **geoengineering** as geo- from the Greek root *ge* meaning earth and engineering meaning "the application of science to the optimum conversion of the resources of nature to the uses of humankind" (16).

2.2 Geoengineering and Carbon Management

The long-term use of fossil energy without emissions of CO_2 is an energy path that may substantially lower the economic cost of mitigating anthropogenic climate change. I call the required technologies ICM, defined as the linked processes of capturing the carbon content of fossil fuels while generating carbon-free energy products such as electricity and hydrogen and sequestering the resulting CO_2.

The distinction between ICM and **geoengineering** is both imprecise and interesting. In drawing the distinction we may first consider climatic geoengineering as a category of response to the CO_2-climate problem. Figure 1 shows a simple schematic of the climate problem for which the response strategies are mitigation, **geoengineering**, or adaptation. In this scheme **geoengineering** is any manipulation of the climate system that alters its response to anthropogenic forcing; the status of ICM is unclear because it resembles both conventional mitigation and **geoengineering**.

The definition adopted here emerges from an elaboration of the three-part schematic. It permits a clear distinction between mitigation of fossil fuel consumption and mitigation of CO_2 emissions, and it draws the line between ICM and **geoengineering** at emission of CO_2 to the active biosphere. Figure 2 shows a four-part schematic that illustrates the definition. It focuses on CO_2, ignoring other anthropogenic climate forcings, and distinguishes between control of CO_2

Figure 1 Three-part schema of the climate problem. The *horizontal arrows* in the *top row* show the causal chain in this version of the anthropogenic climate problem. The *vertical arrows* and the *bottom row* define the modes of intervention.

Figure 2 Four-part schema of the climate problem. The interpretation follows that of Figure 1. Note the distinction between mitigation of fossil energy use, carbon management, and **geoengineering** that illustrate the definition described in Section 2.

emissions to the active biosphere (ICM) and control of atmospheric CO_2 post-emission (**geoengineering**). The implications of this distinction are discussed in the concluding section of the review.

3. HISTORY

3.1 Introduction

Whereas the term **geoengineering** is an invention of the past few decades, explicit consideration of intentional large-scale manipulation of the environment has a history measured in centuries. This review focuses on the post–World War II history

tory measured in centuries. This review focuses on the post–World War II history of weather and climate modification as a direct precursor to current thinking about **geoengineering**. Modern understanding of the CO_2-climate problem emerged at a time when climate and weather modification was an important focus of science policy. My aim is to explore the implications of this background for the treatment of proposals to employ countervailing measures in response to the CO_2-climate problem.

Although the focus here is post–World War II, the link between scientific understanding of the CO_2-climate connection and proposals for its manipulation extends to the beginning of the twentieth century. Writing around 1905, Arrhenius speculated about a virtuous circle in which CO_2 emissions from a growing fossil-fueled civilization would warm the climate, pushing back the northern limits of agriculture and so enhancing agricultural productivity as required to sustain the growth in population (17). Similarly, Eckholm discussed the beneficial effects of elevated CO_2, including effects on both climate and on plant growth, and speculated about the possibility of climate modification via engineered enhancements of CO_2 emission (18).

The historical sketch presented here is necessarily incomplete, and its weaknesses highlight the absence of a thorough historical treatment of deliberate climate modification. Whereas there are modern intellectual histories of climate change (19), and treatments of climate and weather modification that date from

the 1970s (20, **21**), there is little modern analysis that explores the links between weather and climate modification and current concerns about climate change (22).

As we will see, "weather and climate modification" or "weather control" was a centerpiece of research in the atmospheric sciences during the 1950s and 1960s, and was viewed as a priority by the governments of the United States and the USSR. In that context, what are now called climate impacts was then called inadvertent climate modification; and, what is now called **geoengineering** bears a strong similarity to what was then called weather and climate modification.

We may ask, what degree of continuity exists between the older concerns about deliberate and inadvertent climate modification and current concerns about climate impacts and **geoengineering**? With respect to inadvertent climate modification, the case for continuity is strong. Consider, for example, the NAS66 report titled *Weather and Climate Modification* (73) (see Table 1 for definitions of the NASXX style mnemonics). The report contains an excellent summary of the CO_2-climate problem in a chapter titled "Inadvertent Modification of Atmospheric Processes." This is the first extensive treatment of the climate problem in an NAS document, and it shares language and authorship with *Restoring the Quality of Our Environment* (PSAC65) (74), an early and influential assessment of the CO_2-climate problem.

The correspondence between the 1960s concern with weather and climate modification and current discussion of **geoengineering** is less precise in that the aim of weather and climate modification was improvement of the natural state or mitigation of natural hazards, whereas the aim of recent **geoengineering** proposals is the mitigation of anthropogenic hazards. Weather and climate modification therefore had two of the three defining attributes (Section 2.1) of **geoengineering**—scale and intent–but not the third, as it was not a countervailing measure. The case for continuity rests on the similarity of proposed technical methods, the continuity of citations to earlier work, a similarity of debate about legal and political problems, and finally, the strong resemblance of climate and weather modification to **geoengineering** as defined here.

3.2 USSR

In the USSR, sustained interest in weather modification predated World War II. Beginning with the establishment of Leningrad's Institute of Rainmaking in 1932, work on cloud modification moved outside the laboratory, with airborne cloud seeding experiments using calcium chloride beginning as early as 1934 and continuing until 1939 (23). Work resumed immediately after the war with tests of cloud seeding using dry ice (1947) and silver iodide (1949). In the 1950s and early 1960s Soviet interest in climate and weather modification reached its zenith. A single experiment during the winter of 1960–1961, for example, is reported to have cleared clouds over an area of 20,000 km^2.

In the United States, despite common use of the phrase "weather and climate modification," the emphasis was almost entirely on weather control, particularly on the enhancement of precipitation. In contrast, in the USSR there was sustained interest in climate modification, although the bulk of the effort was likewise devoted to weather modification. Climate modification appears to have attracted significant government interest and research funding. In 1961, for example, the 22nd Congress of the Soviet Communist Party listed the development of climate-control methods among the most urgent problems of Soviet science (24).

Taking the 51 abstracts on climate modification cataloged by Zikeev as a guide (23), we find that most of the work during this period addressed the possibility of climate change owing to hydrological modifications such as the construction of large reservoirs and the physical or chemical control of evaporation. There was also persistent interest in the grand project of removing the arctic sea ice to warm Russia. The analysis of the day showed that "the annihilation of the ice cover of the Arctic would be permanent: once destroyed it would never be re-established" (25, p. 7).

Plans for global climate modification attracted occasional interest, perhaps the most extravagant being the proposals to place aerosol "Saturn rings" in earth orbit to heat and illuminate the polar regions. Independent proposals in 1958 and 1960 called for the injection of metallic aerosols into near-earth orbit to form rings that would supply heat and light to northern Russia or would shadow equatorial regions to provide their inhabitants with the supposed benefits of a temperate climate (26).

The triumphant tone of Soviet thinking during the period is well captured in the concluding paragraph of *Man Versus Climate* (26).

> Our little book is now at an end. We have described those mysteries of nature already penetrated by science, the daring projects put forward for transforming our planet, and the fantastic dreams to be realized in the future. Today we are merely on the threshold of the conquest of nature. But if, on turning the last page, the reader is convinced that man can really be the master of this planet and that the future is in his hands, then the authors will consider that they have fulfilled their purpose.

In the absence of a thorough historical study, one may speculate about the roots of post-war Soviet interest in climate modification. Three preconditions seem relevant: (*a*) a social climate in which demonstration of technological power expressed in rapid industrial expansion and in the space race was central to state ideology, (*b*) a climate that is harsh by European standards, and finally, (*c*) the existence of relevant scientific expertise.

Discussions of inadvertent climate modification, and of the potentially harmful side effects of deliberate modifications, punctuate the Soviet literature on climate and weather modification as they did in the United States. For example, perhaps the earliest proposal to engineer a cooling to counter the climatic warming caused by industrial progress was made in 1964 (23), roughly coincident with similar proposals in the United States.

3.3 United States

The 1946 discovery of cloud seeding by Schaefer & Langmuir (27) at the General Electric research labs ignited a commercial boom in weather modification. 2
Within five years private cloud seeding ventures had total annual receipts of $3–5 million, and in 1951 had targeted an area equal to 14% of the landmass of the lower 48 states (ACWC56) (28). The boom rapidly attracted government attention with the first court case involving liability for cloud seeding occurring in 1950, the first senate hearings in 1951, and the formation by congress of the Advisory Commission on Weather Control in 1953.

In the late 1950s weather modification became entangled in the politics of the cold war. Instead of regulating a growing industry, the focus became national security, and during the next decade the issue moved to the top drawer of national science politics. Apparently central to this transformation was growing knowledge of the Soviet effort in the area, combined with concern about the possibility of superior Soviet scientific accomplishment marked by the launch of Sputnik in 1957.

Henry Houghton, the chair of the MIT meteorology department, summarized these fears in an influential 1957 address:

> Man's material success has been due in large degree to his ability to utilize and control his physical environment. ...As our civilization steadily becomes more mechanized and as our population density grows the impact of weather will become ever more serious. ...The solution lies in ... intelligent use of more precise weather forecasts and, ideally, by taking the offensive through control of weather.

Of Soviet effort he said, "I shudder to think of the consequences of a prior Russian discovery of a feasible method for weather control. Fortunately for us and the world we were first to develop nuclear weapons ... International control of weather modification will be as essential to the safety of the world as control of nuclear energy is now." He concluded, "Basic research in meteorology can be justified solely on the economic importance of improved weather forecasting but the possibility of weather control makes it mandatory" (28, 2:286).

During the 1960s federal support for weather and climate modification grew rapidly, reaching $10 million by the decade's end. A series of NAS and NSF reports echoed—and occasionally quoted—Houghton's claims, confirming the central importance of the topic in the atmospheric sciences and repeating concerns about Soviet leadership in the area (e.g. NAS66).

In the United States, the focus was on weather, with large-scale climate modification receiving distinctly less attention than it did in the USSR. Occasional counter examples stand out as in a 1958 paper in *Science*, the head of meteorological

[2] Contemporary documents and more recent historical summaries ignore prior work in the USSR.

---

research at the United States weather bureau speculated about the use of nuclear explosives to warm the arctic climate via the creation of infrared reflecting ice clouds (29).

By 1966 theoretical speculation about use of environmental modification as a tool of warfare (22, 30) became realized as the United States began a campaign of cloud seeding in Vietnam that ultimately flew more than 2600 sorties and had a budget of $3.6 million/year. Public exposure of the program in 1972 generated a rapid and negative public reaction, and lead to an international treaty, the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (31).

The gradual demise of weather modification after the mid-1970s may, arguably, be attributed to three forces: (*a*) backlash against the use of weather modification by the U.S. military, (*b*) the growing environmental movement, and (*c*) the growing realization of the lack of efficacy of cloud seeding.

Beginning in the early 1960s, concerns about CO_2-induced climate change and other forms of inadvertent climate modification became interwoven with work on climate and weather modification. The gradual shift in concern is evident in NAS documents charged with planning the research **agenda** for the atmospheric sciences (32, 33) and in the history of climate assessments that is the topic of Section 3.5.

3.4 Terraforming

Terraforming is "planetary engineering specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life" (34, p. 9). The topic is relevant to assessment of **geoengineering** because the terraforming literature is remarkably broad. In addition to technical papers in mainstream scientific publications (35–37), it includes popular fiction and work by environmental philosophers that examines the moral implications of planetary engineering (39). Though fragmentary, this work compliments the **geoengineering** literature, which is almost exclusively technical. They are linked by commonality of proposed technologies, ethical concerns, and by their ambiguous position between the realms of science fiction and reasoned debate about human use of technology.

Speculation about **geoengineering**—in the form of climate and weather control—and about terraforming both emerged in the 1950s during an era of technological optimism. The history of terraforming is well summarized by Fogg (34). Both the concept of terraforming and the term itself originated in science fiction of the 1940s and 1950s. In 1961 a paper by Sagan in *Science* momentarily brought speculation about terraforming into the "respectable" scientific literature, with a suggestion that "planetary engineering" of Venus could be accomplished by seeding its clouds with photosynthetic microbes to liberate O_2 from CO_2 (36). Another paper by Sagan, in 1973, considered terraforming Mars via alteration of the polar cap albedo using dark dust or living organisms (37). Beginning in the

mid 1970s, a small community of research on and advocacy of terraforming grew around a nucleus of professional planetary scientists. Though clearly at the margins of the scientific mainstream, the terraforming community has nevertheless been able to generate a remarkable continuity of dialogue.

Interestingly, the terraforming community has generated a more robust debate about ethical concerns than exists for **geoengineering**. Rolston and Callicott, for example, have separately attempted to integrate a value for extraterrestrial life into their separate conceptions of a terrestrial environmental ethic

(38).

3.5 Geoengineering in Assessments

Arguably the first high-level government policy assessment that stated the CO_2-climate problem in modern terms was *Restoring the Quality of Our Environment* issued in 1965 by Johnson's Science Advisory Committee (PSAC65). (74) The report combines analysis of atmospheric CO_2 content based on the then □6 year record of accurate measurements with estimates of global fossil fuel combustion to estimate future concentrations. It then combines concentration estimates with early radiative convective models to estimate temperature change and compares that estimate to observed changes with consideration given to intrinsic climate variability. Finally, it speculates about possible impacts beyond temperature, e.g., CO_2 fertilization of plant growth. In concluding the section of the report devoted to climate, the sole suggested response to the "deleterious" impact of CO_2-induced climate change is **geoengineering**: "The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored." The report continues with analysis of a scheme to modify the albedo by dispersal of buoyant reflective particles on the sea surface, concluding, "A 1% change in reflectivity might be brought about for about $500 million a year... Considering the extraordinary economic and human importance of climate, costs of this magnitude do not seem excessive." The possibility of reducing fossil fuel use is not mentioned.

It is interesting to note that the NAS report on climate and weather modification (NAS66)(73), though it was written contemporaneously with PSAC65 (74), does not suggest use of climate modification to counteract human impacts, although it does contain a fair summary of the CO_2-climate problem in its chapter on "Inadvertent Modification of Atmospheric Processes."

The *Study of Critical Environmental Problems* (SCEP70) (75) and the subsequent *Study of Man's Impact on Climate* (SMIC71) (76), both led by MIT during 1970-1971, reflect a sharp break with the tone of optimism about technology that marks the meteorology assessments of the 1960s. Both reports include broad statements that exemplify the emerging environmental consciousness. SMIC (71), for example, notes the increasing demands "man" places on "fragile biological systems" and asks, "How much can we push against the balance of nature before it is seriously upset?" Neither report devotes significant attention to possible responses to the CO_2-climate problem, although SCEP70 does note that reduction in fossil

fuel consumption is the only solution and cites nuclear energy as the sole alternative. Neither report suggests countervailing measures (**geoengineering**). SMIC (71) explicitly considers weather and climate modification as a potential environmental threat, noting that "like so many human endeavors, cloud seeding is showing evidence of unexpected side effects," and recommending "that an international agreement be sought to prevent large-scale[3] ...experiments in persistent or long-term climate modification."

The release of the NAS report *Energy and Climate* (NAS77) (47) coincided with an increasing federal research and assessment effort on the CO_2-climate issue centered at the Department of Energy. It marks the beginning of a continuing chain of NAS reports on the topic that are linked by shared authorship, and explicit cross-references [e.g. NAS79 (77), NAS83 (78), NAS92 (15)]. Like PSAC65, the report linked projections of fossil fuel consumption with models of the carbon cycle and the climate to estimate future climate change. In contrast to SCEP70 and SMIC71, and like PSAC65, **geoengineering** was again on the **agenda**. The fourth of four "crucial" questions listed in the introduction to NAS77 is "What, if any, countervailing human actions could diminish the climatic changes or mitigate their consequences?" Several possibilities were examined, including fertilization of the ocean surface with phosphorus, engineered increases in planetary albedo (citing PSAC65), and massive afforestation with subsequent preservation of woody biomass. However, the report is less optimistic than PSAC65 about countervailing measures and concludes that mitigation via "increased reliance on renewable resources ... will emerge as a more practical alternative." Though not given prominence, the report concludes its introductory statement with an implicit taxonomy of responses that presages the formal taxonomy in NAS92 seen in Figure 2: "If the potential for climate change ... is further substantiated then it may be necessary to (*a*) reverse the trend in the consumption of fossil fuels. Alternatively, (*b*) carbon dioxide emissions will somehow have to be controlled or (*c*) compensated for" (47, p. 3) (enumerations added).

Geoengineering in its most recent incarnation, as a means of counteracting CO_2-induced climate change, receives its most serious airing in the NAS reports of 1983 and 1992.

NAS83 articulated a general framework for understanding the implications of climate change. The explicit aim of the framework was to broaden the debate beyond CO_2, to examine the spatial and temporal inequalities in the distribution of impacts, and finally to examine the problem dynamically over an extended time scale. The report considered measures of CO_2 control separately from countervailing climate modification. With respect to CO_2 control NAS82 notes the importance of the distinction between pre- and postemission CO_2 control and discusses postemission sequestration in terrestrial and oceanic ecosystems, including the burial of trees at sea to effect more permanent sequestration. With respect to countervailing measures NAS83 notes that "in principle weather and climate modification are feasible; the question is only what kinds of advances ... will emerge over the

[3] Large scale was specified as $>10^6$ km^2.

coming century," and adds that "interest in CO_2 may generate or reinforce a lasting interest in national or international means of climate and weather modification;

once generated, that interest may flourish independent of whatever is done about CO_2" (78, p. 470). Finally, NAS83 speculated about the political consequences arising from the possibility of unilateral action to engineer the climate.

In contrast to the NAS83 report, NAS92 made less effort in the direction of an overarching framework. Rather, it focused on detailed technical analysis and included a chapter titled "**Geoengineering**" that included detailed analysis of a diverse array of options. NAS92 did contain a brief three part taxonomy of response strategies like that presented in Figure 1, in which CO_2 capture from the atmosphere (postemission) is considered **geoengineering** and in which sequestration of CO_2 from industrial systems is grouped with other methods of reducing emissions from the energy system. In a synthesis chapter, NAS92 heroically attempted a uniform comparison of the cost effectiveness of all mitigation options including **geoengineering** and presented aggregate mitigation supply curves for many options—a comparison that has not since been repeated.

In the chapter titled "**Geoengineering**," NAS92 analyzed four options: reforestation, ocean fertilization, albedo modification, and removal of atmospheric chlorofluorocarbons. Multiple cost estimates were presented for reforestation, oceanic fertilization with iron, and albedo modification with space-based mirrors or with aerosols in the stratosphere or troposphere. The chapter's introduction included a discussion of predictability and risk assessment, comparing the risk of geoengineering to the risk of inadvertent climate modification. A summary of steps toward further assessment suggested small-scale experiments and the study of side effects including consideration of reversibility and predictability. The chapter ends by observing that "perhaps one of the surprises of this analysis is the relatively low costs at which some of the **geoengineering** options might be implemented," and concluded that "this analysis does suggest that further inquiry is appropriate."

Beginning in the late 1980s the trickle of climate assessments became a flood. Most recent assessments mention **geoengineering** peripherally or not at all (Table 1). I conclude this survey of assessments with a summary of first and second assessment reports (FAR and SAR) of the IPCC. The TAR contains a section provisionally titled "Biological uptake in oceans and fresh-water reservoirs; and **geoengineering**." While it includes some new technical details, the TAR will not significantly improve on the SAR's assessment of **geoengineering**.

The FAR dealt with mitigation in the report of WGIII (IPCC90) (81), whose sole charge was to "formulate response strategies." The report adopts an abstract tone and contains little detailed economic or technical analysis. Neither the FAR nor the SAR include a general framework for categorizing of response strategies as was done in the NAS studies of 1977, 1982, and 1992. The FAR mentions the possibility of "CO_2 separation and geological or marine disposal" as a long-term option but does not describe the possibility further. Enhancement of natural carbon sinks are discussed only for forestry, and as an aside to a more detailed discussion of preventing further emissions by slowing deforestation.

TABLE 1 Selected climate assessments

Mnemonic [a]	**Ref.**	**Title**	**Notes** [b]
ACWC57	28	Advisory Committee on Weather Control	Efficacy of weather control legal; implications; peripheral mention of deliberate and inadvertent climate modification.
WCM66	73	Weather and Climate Modification: Problems and Prospects	Focus on weather, but extended discussion of deliberate and inadvertent climate modification including the CO_2-climate problem.
PSAC65	74	Restoring the Quality of our Environment	Seminal modern statement of the CO_2-climate problem. Countervailing measures were the only mitigation method considered.
SCEP70	75	Study of Critical Environmental Problems	Detailed examination of CO_2-climate problem as one of a small set of critical environmental problems.
SMIC71	76	Study of Man's Impact on Climate: Inadvertent Climate Modification	Very little on mitigation. Concern for the impacts of weather modification.
NAS77	47	Energy and Climate	Stressed importance of limiting fossil emissions and of understanding countervailing measures.
NAS79	77	Carbon Dioxide and Climate: A Scientific Assessment	Focus on estimating climate sensitivity; mitigation was not addressed.
NAS83	78	Changing Climate	General framework of responses to climate change includes countervailing measures and CO_2 control. General discussion of methods; little technical analysis.
EPA83	72	Can We Delay a Greenhouse Warming?	Focus on mitigation in energy sector. Terrestrial sequestration, countervailing measures, and ocean CO_2 injection covered as "Nonenergy Options."
NAS92	15	Policy Implications of Greenhouse Warming	Included a chapter titled **geoengineering** that considered many options and attempted to estimate marginal CO_2-equivalent mitigation costs.

(*Continued*)

TABLE 1 (*Continued*)

Mnemonic [a]	**Ref.**	**Title**	**Notes** [b]
OTA91	79	Changing by Degrees: Steps to Reduce Greenhouse Gases	Focus on mitigation in energy sector. Analysis of carbon sequestration by afforestation.
EPA90	80	Policy Options for Stabilizing Global Climate	Only mitigation in energy sector considered.
IPCC90	81	The IPCC Response Strategies	No general framework for response strategies; CO_2 capture and enhancing forest sinks get minor mentions.
IPCC95	2	Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analysis	No general framework for response strategies; terrestrial sinks covered extensively, oceanic sinks and **geoengineering** mentioned peripherally.

[a] Note the definition of the NASxx style mnemonics used in the text.

[b] The notes are focused on the treatment **geoengineering**.

Working Groups were reorganized for the SAR, with WGII charged with scientific and technical analysis of mitigation. WGII treated enhancement of terrestrial sinks in separate chapters devoted to forests and agricultural lands, and covered capture and sequestration of industrial carbon emission in the chapter on mitigation in the energy sector. The WGII report (IPCC95) (2) included a 3-page section (□0.3% of the report) on “Concepts for Counterbalancing Climate Change.” The text is primarily descriptive, presenting a taxonomy[4] and review of geoengineering methods, including enhancements to the oceanic carbon sink, alteration of albedo, and manipulation of feedback mechanisms. The SAR does not address the question of why enhancement of terrestrial carbon sinks is treated as mitigation whereas enhancement of oceanic sinks is treated as **geoengineering**. In contrast to NAS92 there is no attempt at cost estimation, nor is there mention of broad ethical implications of **geoengineering**. Risks and uncertainties are stressed, but again in contrast to NAS92, no general heuristics for assessing risk (e.g. comparison of the magnitude of natural to engineered effect) are mentioned. Despite the absence of any cost calculations or attempts at risk assessment, the WGII report and the SAR “Summary for Policy Makers” conclude that **geoengineering** is “likely

[4] The first two elements of the SAR’s four-part taxonomy are identical to “albedo” and “emissivity” categories used here (Figure 3). The third element of the SAR’s taxonomy covers all of the “energy transport” category. The fourth element, “counteracting the harmful effects of changes that do occur” represents a different view of the problem from that presented here.

to be ineffective, expensive to sustain and/or to have serious environmental and other effects that are in many cases poorly understood" (2, p. 18).

For the SAR, WGIII was charged with assessing the socio-economic dimensions of climate change and was specifically instructed to "be comprehensive, cover[ing] all relevant sources, sinks and reservoirs of greenhouse gases" (82:ix). The report, however, contains no analysis of **geoengineering** per se. It briefly mentions sequestration of carbon from industrial sources, but does not address any socio-economic implications of issues raised by those technologies, such as the gradual re-release of sequestered carbon. The possible enhancement of ocean carbon sinks is not addressed, and whereas enhancement of terrestrial sinks is considered, little discussion of the social, economic, and biological consequences of the enhancement is presented.

4. TAXONOMY AND REVIEW OF PROPOSALS TO MANIPULATE THE CLIMATE

4.1 Taxonomy

The myriad proposals to geoengineer the climate may usefully be classified by their mode of action (Figure 3). The root division is between alteration of radiative fluxes to regulate the net thermal energy input and alteration of the internal dynamics that redistribute energy in the climate system.[5] The overwhelming majority of **geoengineering** proposals aim to alter radiative energy fluxes, either by increasing the amount of outgoing infrared radiation through reduction of atmospheric CO_2, or by decreasing the amount of absorbed solar radiation through an increase in albedo. With more generality we subdivide alteration of radiative energy fluxes into alteration of thermal (long-wave) radiation or solar (short-wave) radiation. Proposals to alter internal dynamics have focused on the oceans or on surface/atmosphere interaction and are subdivided accordingly in Figure 3. Here we focus on the means of climate modification in general—either deliberate or inadvertent—whereas the categorization illustrated in Figure 2 describes responses to anthropogenic climate change. Figure 3 emphasizes this point by including a classification of human impacts on climate to stress the strong relationship between impacts and **geoengineering**.

With respect to **geoengineering** aimed at countering CO_2-induced global change, there is a fundamental difference between controlling CO_2 and controlling its effects. Albedo modification schemes aim to offset the effect of increasing CO_2

[5] Some treatments use a forcing/feedback division in place of the energy-inputs/internal-dynamics division used here (2), however this is not as precise because internal feedbacks (e.g. ice-albedo feedback) modify the energy input.

(e.g., ice-albedo feedback) modify the energy input.

,
appear
valently
modification
modes
some
climate
of that
modification—equi
Note
modes
The
climate
of
ertent modification.
modes
inadv
the
and climate
of
aim
organizes
deliberate
primary
taxonomy modification.
the
The
with
climate climate both
of
ertent
proposed
modification.
forcing inadv
ebeen as
climate hav and
of
anthropogenic
for
Taxonomy
geoengineering **geoengineering**
e3 as as
Fig possibilities

on the global radiative balance, and thus on average surface temperatures; climatic change may, however, still occur due to changed vertical and latitudinal distributions of atmospheric heating (Section 4.2.1). Moreover, increased CO_2 has substantial effects on plant growth independent of its effect on climate—an effect that cannot be offset by an increase in albedo. In addition, modification of albedo using shields in space or in the stratosphere would reduce the sunlight incident on the surface. The possible effects of this reduction on ecosystem productivity have not been examined.

4.2 Energy Balance: Albedo

4.2.1 Aim and Effect of Albedo Modification It has long been suggested that albedo **geoengineering** aimed at countering the climatic effects of increased CO_2 would produce significant alterations in climate even if perfect control of mean surface temperature were achieved (4, 39, 40). A recent numerical experiment, however, has demonstrated that modification of albedo can compensate for increased CO_2 with remarkable fidelity.

Govindasamy & Caldeira (9) tested the effects of albedo **geoengineering** using a high quality model known to do a good job of simulating the global radiative balance.[6] They compared a control case with two tests cases, one with $2 \times CO_2$ and the other a "**geoengineering**" case with $2 \times CO_2$ and a reduction of solar constant by 1.8%. (Uniform modification of planetary albedo accomplished using scattering systems in space or in the stratosphere would produce a climatic effect equivalent to an alteration of the solar constant, the solar flux at the top of the atmosphere.) By design, the **geoengineering** case had (almost) the same mean surface temperature as the control. Surprisingly, the spatial pattern of surface temperature showed little change despite the changed vertical and latitudinal distributions of atmospheric heating. Compared to the control, the **geoengineering** case produced statistically significant temperature changes over only 15% of the globe as compared to 97% for the $2 \times CO_2$ case. Contrary to expectations, there was very little change in the amplitude of the diurnal and seasonal cycles in the **geoengineering** case.

Although a single numerical experiment does not prove the case, it nevertheless suggests that the climate is less sensitive to changes in the meridional distribution of heating than is often assumed, and therefore the assumption that albedo **geoengineering** could not do an effective job of countering CO_2-induced climate change must be reexamined.

4.2.2 Atmospheric Aerosols Aerosols can increase albedo either directly by optical scattering or indirectly by acting as cloud condensation nuclei that increase

[6] They used version 3 of the Community Climate Model (CCM3) at a horizontal resolution of T42 with 18 vertical layers, run with interactive sea ice coupled to a slab ocean. The $2 \times CO_2$ climate sensitivity was 1.75 C in this configuration. The simulations were run for 40 model years.

---

the albedo and lifetime of clouds by decreasing the mean droplet size. The modification of climate via alteration of cloud and aerosol properties was first proposed in the 1950s (Section 3). The most famous early proposal was by Budyko, who suggested increasing the albedo to counter CO_2-induced climate change by injecting SO_2 into the stratosphere where it would mimic the action of large volcanoes on the climate (41). He calculated that injection of about 10^7 t tons per annum into the stratosphere would roughly counter the effect of doubled CO_2 on the global radiative balance. The NAS92 study showed that several technologically straightforward alternatives exist for injecting the required mass into the stratosphere at low cost.

As with other **geoengineering** proposals, deliberate and inadvertent climate modification are closely linked: Anthropogenic sulfate aerosols in the troposphere currently influence the global radiation budget by □1 Wm^{-2} (watts per square meter)—enough to counter much of the effect of current anthropogenic CO_2.

Addition of aerosol to the stratosphere could have serious impacts, most notably, depletion of stratospheric ozone. Recent polar ozone depletions have clearly demonstrated the complexity of chemical dynamics in the stratosphere and the resulting susceptibility of ozone concentrations to aerosols. Although the possibility of this side effect has long been noted (4, 41, 42), no serious analysis has been published. In addition, depending on the size of particles used, the aerosol layer might cause significant whitening of the daytime sky. This side effect raises one of the many interesting valuation problems posed by **geoengineering**: How much is a blue sky worth?

Recent work by Teller et al (8, 43) has reexamined albedo **geoengineering**. In agreement with NAS92, Teller et al found that 10^7 t of dielectric aerosols of □100 nm diameter are sufficient to increase the albedo by □1%, and they suggested that use of alumina particles could minimize the impact on ozone chemistry. In addition, Teller et al (8) demonstrated that use of metallic or optically resonant scatterers could greatly reduce the total mass of scatterers required. Two configurations of metallic scatterers were analyzed: mesh microstructures and micro-balloons. Conductive metal mesh is the most mass-efficient configuration[7]. In principle, only □10^5 t of such mesh structures are required to achieve the benchmark 1% albedo increase. The proposed metal balloons have diameters of □4 mm, are hydrogen filled, and are designed to float at altitudes of □25 km. The required mass is □10^6 t. Because of the much longer stratospheric residence time of the balloon system

t. Because of the much longer stratospheric residence time of the balloon system, the mass flux (t /yr) required to sustain the two systems is comparable. Finally, Teller et al (8) show that either system, if fabricated with aluminum, can be designed to have long stratospheric lifetimes, yet oxidize rapidly in the troposphere, ensuring that few particles are deposited on the surface.

[7] The thickness of the mesh wires is determined by the skin-depth of optical radiation in the metal (about 20 nm). The spacing of wires (□300 nm) must be □1 /2 the wavelength of scattered light.

It is unclear whether the cost of the novel scattering systems will be less than that of the older proposals, as is claimed by Teller et al (8) because although the system mass is less, the scatterers will be more costly to fabricate. However, it is unlikely that cost would play any significant role in a decision to deploy stratospheric scatterers because the cost of any such system is trivial compared to the cost of other mitigation options. The importance of the novel scattering systems is not in minimizing cost, but in their potential to minimize risk. Two of the key problems with earlier proposals were the potential impact on atmospheric chemistry and the change in the ratio of direct to diffuse solar radiation with the associated visual whitening of the sky. The new proposals suggest that the location, scattering properties, and chemical reactivity of the scatterers could, in principle, be tuned to minimize both impacts.

4.2.3 Planetary Engineering from Space Proposals to modify the climate using space-based technology reflect an extreme of confidence in human technological prowess. Fittingly, some of the grandest and earliest such proposals arose in the USSR immediately following the launch of Sputnik (Section 3.1). During the 1970s, proposals to generate solar power in space and beam it to terrestrial receivers generated substantial interest at NASA and among space technology advocates. Interest in the technology waned under the light of realistic cost estimates, such as the 1981 NAS analysis (43a).

In principle, the use of space-based solar shields has significant advantages over other **geoengineering** options. Because solar shields effect a "clean" alteration of the solar constant, their side effects would be both less significant and more predictable than for other albedo modification schemes. For most plausible shield geometries, the effect could be eliminated at will. Additionally, steerable shields might be used to direct radiation at specific areas, offering the possibility of weather control.

The obvious geometry is a fleet of shields in low-earth orbit (NAS92). However, solar shields act as solar sails and would be pushed out of orbit by the sunlight they were designed to block. The problem gets worse as the mass density is decreased in order to reduce launch costs. A series of studies published in 1989–1992 proposed locating the shield(s) just sunward of the L1 Lagrange point between the Earth and sun, where they would be stable with weak active control (44, 45).

Teller et al (8) note that a scattering system at the L1 point need only deflect light through the small angle required for it to miss the earth, about 0.01 rad as compared to □1 rad for scatterers in near earth orbit or in the stratosphere. For appropriately designed scattering systems, such as the metal mesh described above, the reduced angular deflection requirement allows the mass of the system to decrease by the same ratio. Thus, while a shield at the L1 point requires roughly the same area as a near-earth shield, its mass can be □10^2 times smaller. Teller et al estimate the required mass at □3×10^3 t. The quantitative decrease in mass requirement suggested by this proposal is sufficient to warrant a qualitative

---

change in assessments of the economic feasibility of space-based albedo modification.

The cost of this proposal has not been seriously analyzed. An optimistic order-of-magnitude estimate is $50–500 billion[8]. Arguably, the assumptions about space technology that underlie this estimate could also make space solar power competitive.

4.2.4 Surface Albedo The most persistent modern proposals for large-scale engineering of surface albedo were the proposals to create an ice-free Arctic Ocean to the supposed benefit of northern nations (23, 25) (Section 3.1).

Modification of surface albedo was among the first **geoengineering** measures proposed to counter CO_2-induced warming. For example, the possibility of increasing the oceanic albedo was considered in a series of US assessments (PSAC65, NAS77, and NAS92). Proposals typically involved floating reflective objects, however, “the disadvantages of such a scheme are obvious” (47, p. 13). They include contamination of shorelines, damage to fisheries, and serious aesthetic impacts. Local modification of surface albedo accomplished by whitening of urban areas can, however, play an important role in reducing energy used by air conditioning and in adapting to warmer conditions.

4.3 Energy Balance: Emissivity

Control of long-lived radiatively active gases is the only important means of controlling emissivity[9]. We focus here on CO_2. Following the discussion in Section 2.2, we may usefully distinguish between (*a*) reduction in fossil fuel use, (*b*) reduction in CO_2 emission per unit of fossil carbon used, and (*c*) control of CO_2 by removal from the atmosphere. I refer to these as conventional mitigation, carbon management, and **geoengineering**, respectively.

The distinction is sometimes made between technical and biological sequestration, where the former is intended to label preemission sequestration and the later, postemission. This labeling is imprecise, however, because there are proposals for nonbiological capture from the atmosphere (46) and for preemission biological capture in engineered systems (13).

[8] Cost assessment is heavily dependent on expectations about the future launch costs. Current costs for large payloads to low earth orbit (LEO) are about $10,000/kg. Saturn V launches (the largest launcher ever used successfully) cost $6000/kg. The stated goal of NASA's current access to space efforts is to lower costs to $2000/kg by 2010. This proposal requires a minimum of □30 launches of a Saturn V—approximately equal to the cumulative total of payload lifted to LEO since sputnik. I assume (*a*) that the transit to L1 can be accomplished without large mass penalty (perhaps by solar sailing), and (*b*) that average cost of hardware is less than $10,000/kg.

[9] There is little opportunity to modify surface emissivity (typically values are 85%–95% in the mid infrared, and in any case modification has little effect because only a small fraction of surface radiation is transmitted to space. The main gas controlling atmospheric emissivity is water, but no direct means for controlling it have been proposed.

4.3.1 Carbon Capture in Terrestrial Ecosystems The use of intensive forestry to capture carbon as a tool to moderate anthropogenic climate forcing was first proposed in the late 1970s (47, 48). It is now a centerpiece of proposals to control CO_2 concentrations under the FCCC, particularly under the Clean Development Mechanism. The focus of interest has moved beyond forests to other managed ecosystems such as croplands. There is an extensive literature on both the science and economics of such capture; the summary below aims to frame the issue with reference to **geoengineering**.

Four alternatives are considered for disposition of the carbon once it is captured. It may be (*a*) sequestered in situ either in soil or in standing biomass, (*b*) harvested and separately sequestered, (*c*) harvested and burned as fuel, or (*d*) harvested and burned as fuel with sequestration of the resulting CO_2.

In situ sequestration has been the focus of most of the FCCC-related analysis (1, 2, 12). Uncertainty about the duration of sequestration is crucial. For example, recent analysis has demonstrated that changes in management of cropland, such as use of zero-tillage farming, can capture significant carbon fluxes in soils at low cost, but continued active management is required to prevent the return of carbon to the atmosphere by oxidation (12). For both forest and cropland, uncertainty about the dynamics of carbon in these ecosystems limits our ability to predict their response to changed management practices or to climatic change, and thus adds to uncertainty about the duration of sequestration.

Sequestration of harvested biomass was considered in early analyses (15) but has received little attention in recent work, perhaps because use of biomass as a fuel is a more economically efficient means to retard the increase in atmospheric concentration than is sequestration of biomass to offset fossil carbon emissions. Finally, biomass could be used to produce carbon-free energy (H_2 or electricity) with sequestration of the resulting CO_2 (IPCC95). This process illustrates the complexities of the definitions described above, because it combines pre- and postemission capture and combines biological and technical methods.

Recent studies of carbon capture in cropland have identified the possible contributions of genetically modified organisms to achieving increases in carbon capture, and have stressed the importance of further research (12). The U.S. Department of Energy research effort on sequestration currently includes genomic science as an important part of the sequestration research portfolio for both terrestrial and oceanic ecosystems (13).

Use of terrestrial ecosystems to supply energy needs with minimal net carbon emissions—via any combination of sequestration to offset use of fossil fuels or via the use of biomass energy—will demand a substantial increase in the intensity and/or areal extent of land use. Whether captured by silviculture or agriculture, areal carbon fluxes are of order 1–10 tC/ha-yr (tons carbon per hectare per year). If the resulting biomass were used as fuel, the equivalent energy flux would be 0.2–2 W/m^2, where the lower end of each range is for lightly managed forests and the upper end for intensive agriculture. Mean per-capita energy use in the wealthy industrialized world is □5 kW. Thus, approximately one hectare per

---

capita would be required for an energy system based entirely on terrestrial carbon fixation, roughly equivalent to the current use of cropland and managed forest combined.

Is management of terrestrial ecosystems for carbon capture **geoengineering**? As discussed in the concluding section, the ambiguity of the answer provides insight into shifting standards regarding the appropriate level of human intervention in global biogeochemical systems. Considering the defining attributes of **geoengineering** described in Section 2.1, we can describe a land management continuum in which, for example, land management that considers in situ carbon sequestration as one element in a balanced set of goals forms one pole of the continuum, and the large-scale extraction and separate sequestration of carbon from intensively irrigated and fertilized genetically modified crops forms the opposite pole. The land-use requirements discussed above suggest that manipulation of carbon fluxes at a level sufficient to significantly retard the growth of CO_2 concentrations would entail a substantial increase in the deliberate manipulation of terrestrial ecosystems. Put simply, enhancement of terrestrial carbon sinks with sufficient vigor to aid in solving the CO_2-climate problem is plausibly a form of **geoengineering**.

4.3.2 Carbon Capture in Oceanic Ecosystems Carbon can be removed from the atmosphere by fertilizing the "biological pump" that maintains the disequilibrium in CO_2 concentration between the atmosphere and deep ocean. The net effect of biological activity in the ocean surface is to bind phosphorus, nitrogen, and carbon into organic detritus in a ratio of □1:15:130 until all of the limiting nutrient is exhausted. The detritus then falls to the deep ocean, providing the "pumping" effect. Thus, the addition of one mole of phosphate can, in principle, remove □130 moles of carbon. This ratio includes the carbon removed as $CaCO_3$ owing to alkalinity compensation. This first order model of the biology ignores the phosphate-nitrate balance. Much of the ocean is nitrate limited. Adding phosphate to the system will only enhance productivity if the ecosystem shifted to favor nitrogen fixers. In many cases, nitrogen fixation may be limited by iron and other trace metals.

The possibility of fertilizing the biological pump to regulate atmospheric CO_2 was discussed as early as the NAS77 assessment. At first, suggestions focused on adding phosphate or nitrate. Over the past decade it has become evident that iron may be the limiting nutrient over substantial oceanic areas (11, 49). The molar ratio Fe:C in detritus is □1:10,000, implying that iron can be a very efficient fertilizer of ocean-surface biota. Motivated in part by interest in deliberate enhancement of the oceanic carbon sink, two field experiments have tested iron fertilization in situ and have demonstrated dramatic productivity enhancements over the short duration of the experiments (50–52). However, it is not clear that sustained carbon removal is realizable (53).

Ocean fertilization is now moving beyond theory. Recently, a commercial venture, Ocean Farming Incorporated, has announced plans to fertilize the ocean for

the purpose of increasing fish yields and perhaps to claim carbon sequestration credits under the emerging FCCC framework (6:121–29).

Ocean fertilization may have significant side effects. For example, it might decrease dissolved oxygen with consequent increased emissions of methane—a greenhouse gas. In addition, any significant enhancement of microbiological productivity would be expected to alter the distribution and abundance of oceanic macro-fauna. These side effects are as yet unexamined.

4.3.3 Geochemical Sequestration On the longest timescales, atmospheric CO_2 concentrations are controlled by the weathering of magnesium and calcium silicates that ultimately react to form carbonate deposits on the ocean floor, removing the carbon from shorter timescale biogeochemical cycling. In principle, this carbon sink could be accelerated, for example, by addition of calcite to the oceans (54) or by an industrial process that could efficiently form carbonates by reaction with atmospheric CO_2 (46). I call this geochemical sequestration.

In either case, the quantity (in moles) of the required alkaline minerals is comparable to the amount of carbon removed. The quantities of material processing required make these proposals expensive compared to other means of removing atmospheric CO_2.

The most plausible application of geochemical sequestration is as a means to permanently immobilize carbon captured from fossil fuel combustion. Integrated power plant designs have been proposed, in which a fossil fuel input would be converted to carbon-free power (electricity or hydrogen) with simultaneous reaction of the CO_2 with serpentine rock (magnesium silicate) to form carbonates. Carbonate formation is exothermic; thus, in principle, the reaction requires no input energy. Ample reserves of the required serpentine rocks exist at high purity. The size of the mining activities required to extract the serpentine rock and dispose of the carbonate are small compared to the mining activity needed to extract the corresponding quantity of coal. The difficulty is in devising an inexpensive and environmentally sound industrial process to perform the reaction (46).

The importance of geochemical sequestration lies in the permanence with which it removes CO_2 from the biosphere. Unlike carbon that is sequestered in organic matter or in geological formations, once carbonate is formed, the carbon is permanently removed. The only important route for it to return to active biogeochemical cycling is by thermal dissociation following the subduction of the carbonate-laden oceanic crust beneath the continents, a process with a time-scale of $>10^7$ years.

4.3.4 Capture and Sequestration of Carbon from Fossil Fuels The CO_2 generated from oxidation of fossil fuels can be captured by separating CO_2 from products of combustion or by reforming the fuel to yield a hydrogen-enriched fuel stream for combustion and a carbon-enriched stream for sequestration. In either case, the net effect is an industrial system that produces carbon-free energy and CO_2—separating the energy and carbon content of fossil fuels. The CO_2 may then be sequestered in geological formations or in the ocean.

Because the status of carbon management as **geoengineering** is ambiguous and because there is now a large and rapidly growing literature on the subject (55, 56), only a brief summary is included here despite its growing importance. Our focus is on oceanic sequestration because it most clearly constitutes **geoengineering** (Section 2.2).

One may view CO_2-induced climate change as a problem of mismatched timescales. The problem is due to the rate at which combustion of fossil fuels is transferring carbon from ancient terrestrial reservoirs into the comparatively small atmospheric reservoir. When CO_2 is emitted to the atmosphere, atmosphere-ocean equilibration transfers □80% of it to the oceans with an exponential timescale of □300 years (57). The remaining CO_2 is removed with much longer timescales. Injecting CO_2 into the deep ocean accelerates this equilibration, reducing peak atmospheric concentrations. Marchetti used similar arguments in coining the term **geoengineering** in the early 1970s to denote his suggestion that CO_2 from combustion could be disposed of in the ocean (14). Oceanic sequestration is a technical fix for the problem of rising CO_2 concentrations; and it is a deliberate planetary-scale intervention in the carbon cycle. It thus fits the general definition of **geoengineering** given above (Section 2) as well as the original meaning of the term.

The efficiency with which injected CO_2 equilibrates with oceanic carbon depends on the location and depth of injection. For example, injection at □700 m depth into the Kuroshio current off Japan would result in much of the CO_2 being returned to the atmosphere in □100 years, whereas injections that formed "lakes" of CO_2 in ocean trenches might more efficiently accelerate equilibration of the CO_2 with the deep-sea carbonates.

The dynamic nature of the marine carbon cycle precludes defining a unique static capacity, as may be done for geological sequestration. Depending on the increase in mean ocean acidity that is presumed acceptable, the capacity is of order □10^3–10^4 gigatons of carbon (GtC), much larger than current anthropogenic emissions of □6 GtC per year.

In considering the implications of oceanic sequestration one must note that—depending on the injection site—about 20% of the carbon returns to the atmosphere on the □300 year timescale. Supplying the energy required for separating, compressing, and injecting the CO_2 would require more fossil fuel than if the CO_2 was vented to the atmosphere. Thus, while oceanic sequestration can reduce the peak atmospheric concentration of CO_2 caused by the use of a given amount of fossil-derived energy, it may increase the resulting atmospheric concentrations on time-scales greater than the □300 year equilibration time.

4.4 Energy Transport

The primary means by which humanity alters energy transport is by alteration of land surface properties. The most important influence is on hydrological properties, particularly through changes to surface hydrological properties and the rates

of evapo-transpiration, but additionally via dams that create large reservoirs or redirect rivers. A secondary influence is on surface roughness via alteration of land use.

Inadvertent alteration of local and regional climate has already occurred due to alteration of land surface properties via either the means mentioned above or by alteration of albedo (Section 4.2.4). In addition, deliberate alteration of local microclimates is a common feature of human land management. Despite the long record of speculation about the alteration of surface properties with the intention of altering regional or global climate, it seems highly unlikely that **geoengineering** will ever play an important role in land management, given the manifold demands on land use and the difficulty of achieving such large-scale alterations.

Other means of altering energy transport are more speculative. Examples include weather modification and redirection of ocean currents using giant dams. In principle, the direct application of mechanical work to alter atmospheric motions offers an energetically efficient means of weather modification (58); however, no practical means of applying such forces are known. Alternatively, weather modification may be accomplished by cloud seeding. Despite very large cumulative research expenditure over its long history, cloud seeding has demonstrated only marginal effectiveness. Accurate knowledge of the atmospheric state and its stability could permit leverage of small, targeted perturbations to effect proportionately larger alterations of the atmospheric dynamics. The small perturbations could be effected by cloud seeding or direct application of thermal or mechanical energy. The increasing quality of analysis/forecast systems and the development of effective adjoint models that allow accurate identification of dynamic instabilities suggest that the relevant predictive capability is emerging.

5. EVALUATING GEOENGINEERING

Geoengineering is not now seriously incorporated into formal assessments of anthropogenic climate change (e.g. the IPCC). More specifically, (*a*) the word geoengineering is rarely used, (*b*) the methods defined here as **geoengineering** are generally not discussed (with the salient exception of biological sequestration), and finally, (*c*) the implications of deliberate planetary-scale environmental management are not seriously addressed. Where **geoengineering** is discussed, the focus is typically technical, with scant consideration of broader implications such as the appropriate legal and political norms for decision-making and the distribution of risks and benefits. Here I review various framings for the assessment of **geoengineering**, but make no attempt at an overall synthesis.

5.1 Economics

The simplest economic metric for **geoengineering** is the cost of mitigation (COM), where mitigation of any kind is measured as an equivalent quantity of carbon removed from the atmosphere. Table 2 comprises a summary of COM

Page 26

effect
of ved.
each political Sea, Sea,
e islocal, 2 possibility the from ved.
Lik with and disposal. CO the impro
of amethod of be of
legal w arising w arising impro
issues London scheme or La fisheries, La be
vention. oceanic might possibility that
this er on
con associated ov disposal abatement? Treaty Treaty might
Potential concerns concerns

concerns: costs concerns: effect fisheries concerns:
fisheries;
gal dumping without concerns geologic gal Antarctic for that gal Antarctic in fisheries
Nontechnical Is **geoengineering** Le Liability Le Liability

.

may ocean may ocean
release. release.
Possible of Possible of
local
effects
to
Possibility
mix mix
risk depletion risk depletion
community
side
methane methane
of
risk risk.
damage
w w
of benthic oxygen Changed biota oxygen Changed biota
Risk Lo Lo Moderate Moderate

in
wn 2 is there
CO about storage. P:N there
kno ocean. Can
in Can its When
2 for Can
options as
better **geoengineering** oceanic
CO
wn
of uncertainty change ratio? long-term limiting? long-term
uncertainties uncertainty than biology: biology:
much other kno capture? capture?
less
fate
are for are
really
than schemes about ocean geologic ecosystem utilization significant iron significant carbon
geoengineering **Technical** Costs Moderate Costs Uncertain Uncertain
of

*

COM 50–150 50–150 3–10 1–10
comparison

2 2
Summary CO CO
of ocean of
2
ground fertilization fertilization
the phosphate iron

into under with with
TABLE **Geoengineering method** Injection Injection Ocean Ocean

alone.

if
authors
of
control.
to the
strongly
w land are
liability
ho ution
cost

Intensive forestry to capture carbon in harvested trees	10–100	Uncertainty about rate of carbon accumulation, particularly under changing climatic conditions.	Low risk. Intensive cultivation will impact biodiversity and soils.	Political questions: Whose costs? divisions used?
Solar shields to generate an increase in the Earth's albedo	0.05–0.5	Costs are dominated by launch costs. Uncertainty technical feasibility and uncertain.	Low risk. However, albedo does not exactly counter effect of increased CO2, increase risk.	Security, equity, system used for weather and
Stratospheric SO2 to increase albedo by direct scattering	1	Uncertain lifetime of stratospheric aerosols.	High risk. Effect on ozone depletion. Albedo is not equivalent to CO2, ozone uncertain.	Liability: ozone destruction.
Tropospheric SO2 to increase albedo by direct and indirect effects	<1	Substantial uncertainties regarding transport and its aerosol optical properties, and effect on cloud.	Moderate risk: mitigation of CO2 effect, tropospheric ... international progress in	Liability because sovereignty and the distribution of regional aerosols climate.

*Cost of mitigation (COM) is in dollars per ton carbon ($/tc) of CO2 emissions mitigated. Although based on current literature, estimates of the risk and ...

for **geoengineering** computed in accord with the NAS92 methodology. The costs are highly uncertain. For albedo modification schemes, additional uncertainty is introduced by the somewhat arbitrary conversion from albedo change to equivalent reduction in CO_2, which depends on assumptions about the climate's sensitivity to increased CO_2 and on the atmospheric lifetime of CO_2. The estimated COM varies by more than two orders of magnitude between various **geoengineering** methods. It is noteworthy that for some methods, particularly albedo modification, the costs are very low compared to emissions abatement.

In principle, the COM permits a direct comparison among **geoengineering** methods and between **geoengineering** and abatement. In practice, differences in the distribution of costs and benefits as well as the nonmonetary aspects of **geoengineering** render such cost comparison largely irrelevant to real decisions about abatement.

Examination of the shape of the marginal COM functions provides an insightful comparison between **geoengineering** and abatement. Although the COM is uncertain, there is much less doubt about how the COM scales with the amount of mitigation required. First, consider conventional mitigation. Whereas econometric and technical methods for estimating the cost of moderate abatement differ, both agree that costs will rise steeply if we want to abate emissions by more than about 50% (between 100 and 500 $/tC) (2, 15). In sharp contrast, geoengineering the planetary albedo has marginal costs that, although highly uncertain, are roughly independent of, and probably decrease with, the amount of mitigation required.[10] In particular, the COM for albedo modification will not rise steeply as one demands 100% abatement because the process of albedo modification has no intrinsic link to the scale of current anthropogenic climate forcing. One could, in principle, engineer an albedo increase several times larger than the equivalent anthropogenic forcing and thus cool the climate. These relationships are illustrated in Figure 4*A*.

Next, consider industrial carbon management (ICM), defined in the restrictive sense as including preemissions controls only (Section 2.2). For low levels of mitigation, the COM for ICM is higher than for conventional mitigation, but the marginal cost of carbon management is expected to rise more slowly. The addition of ICM to conventional mitigation is thus expected to substantially lower the cost of large emission reductions as is shown schematically in Figure 4*A*. However, no matter how optimistically one assesses ICM technologies, the marginal COM will still rise steeply as one approaches 100% mitigation, owing to the difficulty of wringing the last high-marginal-cost emissions from the energy system.

Finally, consider **geoengineering** of CO_2 by enhancement of biological sinks or by physical/chemical methods. As with albedo modification, there is no link to the

[10] Whereas space-based albedo modification is much more expensive, both stratospheric- and space-based albedo modification have large initial fixed costs and likely decreasing marginal costs.

Figure 4 Schematic comparison between modes of mitigation. (*A*) Conventional mitigation means any method other than **geoengineering** or carbon management, e.g. conservation or use of nonfossil energy. The addition of carbon management lowers the cost of emissions mitigation; however, costs will still rise steeply as one tries to eliminate all emissions. Conversely, albedo modification from space has very high initial capital costs but can provide essentially unlimited-effect low marginal cost. (*B*) Sequestration based on ecosystem modification will have costs that rise steeply at a mitigation amount (carbon flux) set by the internal dynamics of the respective systems.

scale of current anthropogenic emissions. Rather, each kind of sink will have its own intrinsic scale determined by the relevant biogeochemistry. Marginal COM for each sink will rise as one demands an amount of mitigation beyond its intrinsic scale. Figure 4*B* shows examples of plausible marginal cost functions.

Examination of the marginal COM functions illuminates the question of whether enhancement of biological carbon sinks is a form of **geoengineering**. Industrial carbon management is like conventional mitigation in that it is tied to the scale of anthropogenic emissions. In contrast, removal of CO_2 from the atmosphere, either by enhancement of biological sinks or by other methods, is like **geoengineering** of albedo because as a countervailing measure it is independent of the scale of anthropogenic emissions.

Geoengineering might, in principle, be incorporated into integrated assessments of climate change as a fallback strategy that supplies an upper bound on the COM. In this context a fallback strategy must either be more certain of effect, faster to implement, or provide unlimited mitigation at fixed marginal cost. Various **geoengineering** schemes meet each of these criteria. The fallback strategy defined here for integrated assessment is a generalization of a backstop technology used in energy system modeling, where it denotes a technology that can supply unlimited energy at fixed (usually high) marginal cost. Fallback strategies will enter if climate change is more severe than we expect or if the COM is much larger than we expect (4, 15). The existence of a fallback strategy permits more confidence in adopting a moderate response to the climate problem: Without fallback options a moderate response is risky given the possibility of a strong climatic response to moderate levels of fossil-fuel combustion.

5.2 Risk

Geoengineering poses risks that combine natural and social aspects. For example, will stratospheric aerosols destroy ozone? Will the availability or implementation of **geoengineering** prevent sustained action to mitigate climate forcing? Here we focus on the technical risks and defer consideration of social risks to the following section.

The biogeochemical risks differ markedly for the two principal classes of geoengineering strategy—albedo modification and CO_2 control. For each class, risks may be roughly divided into two types; risk of side effect and risk that the manipulation will fail to achieve its central aim. For albedo modification, the division is between side effects such as ozone depletion, that arise directly from the albedo-modifying technology, and risk of failure associated with the difficulty of predicting the climatic response to changes in albedo. Side effects of CO_2 control include loss of biodiversity or loss of aesthetic value that may arise from manipulating ecosystems to capture carbon, and risk of failure is associated with unexpectedly quick re-release of sequestered carbon.

The risks posed by **geoengineering** are sufficiently novel that, in general, the relevant biological and geophysical science is too uncertain to allow quantitative assessment of risk. Absent quantitative assessment, various avenues remain for robust qualitative risk assessment, for example, if a **geoengineering** scheme works by imitating a natural process we can compare the magnitude of the engineered effect with the magnitude and variability of the natural process, and then assume that similar perturbations entail similar results (4, 5, 15). For example, the amount of sulfate released into the stratosphere as part of a **geoengineering** scheme and the amount released by a large volcanic eruption are similar. We may estimate the magnitude of stratospheric ozone loss by analogy.

In decisions about implementation, judgment about the risks of **geoengineering** would depend on the scalability and reversibility of the project: Can the project be tested at small scale, and can the project be readily reversed if it goes awry? These attributes are vital to enabling management of risk through some form of global-scale adaptive ecological management (7, 59). Even crude qualitative estimates of risk can give insight into the relative merits of various **geoengineering** methods when considered in conjunction with other variables (4).

We have examined the risk of **geoengineering** in isolation. More relevant to real choices about planetary management is a comparison of the risks and benefits of **geoengineering** with those of other response strategies. Here we are in unexplored territory as the literature has largely avoided this question. Without attempting such a comparison, we note that it would have to be explicit about the goals; i.e. is **geoengineering** a substitute for abatement, an addition to abatement, or a fallback strategy? Also, it would have to assess the risks of abatement or adaptation per se.

5.3 Politics and Law

The politics of **geoengineering** rests on two central themes: The first emerges from the fact that many **geoengineering** schemes are amenable to implementation by independent action, whereas the second relates to **geoengineering**'s status as a form of moral hazard. First consider independent action. Unlike other responses to climate change (e.g. abatement or adaptation), **geoengineering** could be implemented by one or a few countries acting alone. Various political concerns arise from this fact with respect to security, sovereignty, and liability; they are briefly summarized below.

Some **geoengineering** schemes raise direct security concerns; solar shields, for example, might be used as offensive weapons. A subtler, but perhaps more important security concern arises from the growing links between environmental change and security. Whether or not they were actually responsible, the operators of a **geoengineering** project could be blamed for harmful climatic events that could plausibly be attributed to the project by an aggrieved party. Given the current political disputes arising from issues such as the depletion of fisheries and aquifers, it seems plausible that a unilateral **geoengineering** project could lead to significant political tension.

International law would bear on these security and liability concerns. Bodansky (60) points out that existing laws may cover several specific proposals; for example, the fertilization of Antarctic waters would fall under the Antarctic Treaty System, and the use of space-based shields would fall under the Outer Space Treaty of 1967. In addition, the IPCC95 report argues that many **geoengineering** methods might be covered by the 1977 treaty prohibiting the hostile use of environmental modification (31).

As in the current negotiations under the FCCC, **geoengineering** would raise questions of equity. Schelling has argued that in this case **geoengineering** might simplify the politics; **geoengineering** "...totally transforms the greenhouse issue from an exceedingly complicated regulatory regime to a simple—not necessarily easy but simple–problem in international cost sharing" (61, p. 305).

One must note that not all **geoengineering** methods are amenable to centralized implementation; in particular, most albedo modification methods are, whereas control of greenhouse gases is generally not.

Separate from the possibility of independent action is the concern that geoengineering may present a moral hazard. The root problem is simple: Would mere knowledge of a **geoengineering** method that was demonstrably low in cost and risk weaken the political will to mitigate anthropogenic climate forcing? Knowledge of **geoengineering** has been characterized as an insurance strategy; in analogy with the moral hazard posed by collective insurance schemes, which encourage behavior that is individually advantageous but not socially optimal, we may ascribe an analogous hazard to **geoengineering** if it encourages suboptimal investment in mitigation. As the following examples demonstrate, **geoengineering** may pose a moral hazard whether or not its implementation is in fact a socially optimal strategy. If the existence of low-cost biological sinks encourages postponement of effective action on emissions mitigation and if such sinks prove leaky then the existence of these sinks poses a moral hazard.

To illustrate that **geoengineering** may be optimal yet still present a moral hazard, suppose that two or three decades hence real collective action is underway to reduce CO_2 emissions under a binding agreement that limits peak atmospheric CO_2 concentrations to 600 ppmv (parts per million volume) and which mandates that concentrations will be reduced to less than 450 ppmv by some fixed date. Suppose further that both the cost of mitigation and the climate sensitivity turn out to be higher than we now anticipate and that the political coalition supporting the agreement is just strong enough to sustain the actions necessary meet the concentration targets, but is not strong enough to support lowering of the targets. Finally, suppose that a temporary space-based albedo modification system is proposed that will limit climate impacts during the period of peak CO_2 concentrations. Even if strong arguments can be made that the albedo modification is truly a socially optimal strategy, it may still present a moral hazard if its implementation encourages a retreat from agreed stringent action on mitigation.

The status of **geoengineering** as a moral hazard may partially explain the paucity of serious analysis on the topic. Within the policy analysis community, for example, there has been vigorous debate about whether discussion of **geoengineering**

should be included in public reports that outline possible responses to climate change, with fears voiced that its inclusion could influence policy makers to take it too seriously and perhaps defer action on abatement, given knowledge of **geoengineering** as an alternative (2, 62).

5.4 Environmental Ethics

Discussion of the advisability of **geoengineering** has been almost exclusively limited to statements about risk and cost. Although ethics is often mentioned, the arguments actually advanced have focused on risk and uncertainty; serious ethical arguments about **geoengineering** are almost nonexistent. Many of the objections to **geoengineering** that are cited as ethical have an essentially pragmatic basis. Three common ones are:

1. *The slippery slope argument*. If we choose **geoengineering** solutions to counter anthropogenic climate change, we open the door to future efforts to systematically alter the global environment to suit humans. This is a pragmatic argument, unless one can define why such large-scale environmental manipulation is bad, and how it differs from what humanity is already doing.
2. *The technical fix argument.* **Geoengineering** is a technical fix, kluge, or end-of-pipe solution. Rather than attacking the problems caused by fossil fuel combustion at their source, **geoengineering** aims to add new technology to counter their side effects. Such solutions are commonly viewed as inherently undesirable—but not for ethical reasons.
3. *The unpredictability argument.* **Geoengineering** entails "messing with" a complex, poorly understood system; because we cannot reliably predict results it is unethical to geoengineer. Because we are already perturbing the climate system willy-nilly with consequences that are unpredictable, this argument depends on the notion that intentional manipulation is inherently worse than manipulation that occurs as a side effect.

These concerns are undoubtedly substantive, yet they do not exhaust the underlying feeling of abhorrence that many people feel for **geoengineering**. As a first step toward discussion of the underlying objections one may analyze geoengineering using common ethical norms; for example, one could consider the effects of **geoengineering** on intergenerational equity or on the rights of minorities. Such an analysis, however, can say nothing unique about **geoengineering** because other responses to the CO_2-climate problem entail similar effects. I sketch two modes of analysis that might be extended to address some the underlying concerns about **geoengineering**. The first concerns the eroding distinction between natural and artificial and the second, the possibility of an integrative environmental ethic.

The deliberate management of the environment on a global scale would, at least in part, force us to view the biosphere as an artifact. It would force a reexamination

of the distinction between natural science and what Simon (63) called "the sciences of the artificial"—that is engineering and the social sciences. The inadvertent impact of human technology has already made the distinction between managed and natural ecosystems more one of degree than of kind, but in the absence of planetary **geoengineering** it is still possible to imagine them as clearly distinct (7, 64). The importance of, and the need for, a sharp distinction between natural and artificial, between humanity and our technology was described by Tribe in analyzing concerns about the creation of artificial environments to substitute for natural ones (65, 66).

The simplest formulations of environmental ethics proceed by extension of common ethical principles that apply between humans. A result is animal rights (67) or one of its variants (68). Such formulations locate rights or moral value in individuals. When applied to a large-scale problem such as the choice to geoengineer, an ethical analysis based on individuals reduces to a problem of weighing conflicting rights or utility. As with analyses that are based on more traditional ethical norms, such analysis has no specific bearing on geoengineering.

In order to directly address the ethical consequences of **geoengineering** one might desire an integrative formulation of environmental ethics that located moral value at a level beyond the individual, a theory that ascribed value to collective entities such as a species or a biotic community. Several authors have attempted to construct integrative formulations of environmental ethics (69–71), but it is problematic to build such a theory while maintaining an individualistic conception of human ethics (71), and no widely accepted formulation has yet emerged.

6. SUMMARY AND IMPLICATIONS

A casual look at the past few decades of debate about the CO_2-climate problem might lead one to view **geoengineering** as a passing aberration, an idea that originated with a few speculative papers in the 1970s, that reach a peak of public exposure with the NAS92 assessment and the cotemporaneous American Geophysical Union and American Association for the Advancement of Science colloquia of the early 1990s, an idea that is now fading from view as international commitment to substantive action on climate grows ever stronger. The absence of debate about **geoengineering** in the analysis and negotiations surrounding the FCCC supports this interpretation. However, I argue that this view is far too simplistic. First, consider that scientific understanding of climate has co-evolved with knowledge of anthropogenic climate impacts, with speculation about the means to manipulate climate, and with growing technological power that grants the ability to put speculation into practice. The history of this co-evolution runs through the century, from Eckholm's speculation about the benefits of accelerated fossil fuel use to our growing knowledge about the importance of iron as a limiting factor in ocean ecosystem productivity.

This view of climate history is in accord with current understanding of the history of science that sees the drive to manipulate nature to suit human ends as integral to the process by which knowledge is accumulated. In this view, the drive to impose human rationality on the disorder of nature by technological means constitutes a central element of the modernist program. This link between understanding and manipulation is clearly evident in the work of Francis Bacon that is often cited as a signal of the rise of modernism in the seventeenth century.

Moreover, the disappearance of the term **geoengineering** from the mainstream of debate, as represented by the FCCC and IPCC processes, does not signal the disappearance of the issue. The converse is closer to the truth: Use of the term has waned as some technologies that were formerly called **geoengineering** have gained acceptance.

To illustrate the point, consider the shifting meaning of carbon management. The recent Department of Energy "roadmap," an important agency-wide study of "Carbon Sequestration Research and Development" (13) serves as an example. The report uses a very broad definition of carbon management that includes (*a*) demand-side regulation through improved energy efficiency, (*b*) decarbonization via use of low-carbon and carbon-free fuels or nonfossil energy, and (*c*) carbon sequestration by any means, including not only carbon capture and sequestration prior to atmospheric emission, but all means by which carbon may be captured from the atmosphere. Although the report avoids a single use of the word geoengineering in the body of the text, one may argue from its broad definition of carbon management that the authors implicitly adopted a definition of **geoengineering** that is restricted to modifications to the climate system by any means other than manipulation of CO_2 concentration.

In contrast, I have drawn the line between **geoengineering** and industrial carbon management at the emission of CO_2 to the active biosphere. Three arguments support this definition. First, and most importantly, the capture of CO_2 from the atmosphere is a countervailing measure, one of the three hallmarks of **geoengineering** identified in Section 2.1. It is an effort to counteract emissions, and thus control CO_2 concentrations, through enhancement of ecosystem productivity or through the creation of new industrial processes. These methods are unrelated to the use of fossil energy except in that they aim to counter its effects (Section 5.1). The second argument is from historical usage (Section 3.5); the capture of CO_2 from the atmosphere has been treated explicitly as geoengineering (2–5, 42) or has been classified separately from emissions abatement and grouped with methods that are now called **geoengineering** (47, 72). Finally, the distinction between pre- and postemission control of CO_2 makes sense because it will play a central role in both the technical and political details of implementation.

As a purely semantic debate, these distinctions are of little relevance. Rather, their import is the recognition that there is a continuum of human responses to the climate problem that vary in resemblance to hard **geoengineering** schemes such as

spaced-based mirrors. The de facto redefinition of **geoengineering** to exclude the response modes that currently seem worthy of serious consideration, and to include only the most objectionable proposals, suggests that we are moving down the continuum toward acceptance of actions that have the character of **geoengineering** (as defined here) though they no longer bear the name. The disappearance of **geoengineering** thus signals a lamentable absence of debate about the appropriate extent of human intervention in the management of planetary systems, rather than a rejection of such intervention.

Consider, for example, the perceived merits of industrial and biological sequestration. In the environmental community (as represented by environmental nongovernment agencies) biological sequestration is widely accepted as a response to the CO_2-climate problem. It has been praised for its multiple benefits such as forest preservation and the possible enrichment of poor nations via the Clean Development Mechanism of the FCCC. Conversely, industrial sequestration has been viewed more skeptically as an end-of-pipe solution that avoids the root problems. Yet, I have argued here that biological sequestration–if adopted on a scale sufficient for it to play an important role—resembles geoengineering more than does industrial sequestration. Whereas industrial sequestration is an end-of-pipe solution, biological sequestration might reasonably be called a beyond-the-pipe solution. Such analysis cannot settle the question; it merely highlights the importance of explicit debate about the implications of countervailing measures.

Looking farther ahead, I speculate that views of the CO_2-climate problem may shift from the current conception in which CO_2 emission is seen as a pollutant to be eliminated, albeit a pollutant with millennial timescale and global impact, toward a conception in which CO_2 concentration and climate are seen as elements of the earth system to be actively managed. In concluding the introduction to the 1977 NAS assessment, the authors speculated on this question, asking "In the light of a rapidly expanding knowledge and interest in natural climatic change, perhaps the question that should be addressed soon is, 'What should the atmospheric carbon dioxide content be over the next century or two to achieve an optimum global climate?' Sooner or later, we are likely to be confronted by that issue" (47:ix).

Allenby argues that we ought to begin such active management (7). Moreover, he argues that failure to engage in explicit "earth system engineering and management" will impair the effectiveness of our environmental problem solving. If we take this step, the upshot will be that predicted in NAS82: "Interest in CO_2 may generate or reinforce a lasting interest in national or international means of climate and weather modification; once generated, that interest may flourish independent of whatever is done about CO_2" (47: p. 470).

Although the need for improved environmental problem solving is undeniable, I judge that great caution is warranted. Humanity may inevitably grow into active planetary management, yet we would be wise to begin with a renewed commitment to reduce our interference in natural systems rather than to act by balancing one interference with another.

ACKNOWLEDGMENTS

I thank Alex Farrell, Tim Johnson, Anthony Keith, Granger Morgan, Ted Parson, Peter Reinelt, and Robert Socolow for their useful comments. The work was supported in part by NSF grant SES-9022738.

LITERATURE CITED

1. Bruce JP, Lee H, Haites EF, eds. 1996. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Cambridge, UK: Cambridge Univ. Press
2. Watson RT, Zinyowera MC, Moss RH, eds. 1996. *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses*. Cambridge, UK: Cambridge Univ. Press
3. Flannery BP, Kheshgi H, Marland G, MacCracken MC. 1997. **Geoengineering** climate. In *Engineering Response to Global Climate Change*, ed. RG Watts, pp. 379–427. Boca Raton, FL: Lewis
4. Keith DW, Dowlatabadi H. 1992. Taking **geoengineering** seriously. *Eos, Trans. Am. Geophys. Union* 73:289–93
5. Michaelson J. 1998. **Geoengineering**: a climate change Manhattan project. *Stanford*
10. Cooper DJ, Watson AJ, Nightingale PD. 1996. Large decrease in ocean-surface CO_2 fugacity in response to in situ iron fertilization. *Nature* 383:511–13
11. Behrenfeld MJ, Kolber ZS. 1999. Widespread iron limitation of phytoplankton in the South Pacific Ocean. *Science* 283:840–43
12. Rosenberg NJ, Izaurralde RC, Malone EL. 1998. Carbon sequestration in soils: science, monitoring, and beyond. *Proc. St. Michaels Workshop*. Columbus, Ohio: Battelle
13. Reichle D, Houghton J, Kane B, Ekmann J. 1999. *Carbon Sequestration Research and Development*. *Rep. DOE/SC/FE-1*, US Dep. Energy, Washington, DC
14. Marchetti C. 1977. On **geoengineering** and

Environ. Law J. 17:73–140
6. Kitzinger U, Frankel EG, eds. 1998. *Macro-Engineering and the Earth: World Projects for the Year 2000 and Beyond*. Chichester, UK: Horwood
7. Allenby B. 1999. Earth systems engineering: the role of industrial ecology in an engineered world. *J. Ind. Ecol.* 2:73–93
8. Teller E, Wood L, Hyde R. 1997. *Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change. UCRL-JC-128157*. Livermore, CA: Lawerence Livermore Natl. Lab.
9. Govindasamy B, Caldeira K. 2000. Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change. *Geophys. Res. Lett.* 27(14):2141–44

the CO_2 problem. *Clim. Change* 1:59–68
15. Panel on Policy Implications of Greenhouse Warming. 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base.* Washington, DC: Natl. Acad. Press
16. Gove PB, ed. 1986. *Webster's Third New International Dictionary of the English Language Unabridged.* Springfield, MA: Merriam-Webster
17. Arrhenius S. 1908. *Worlds in The Making: The Evolution of the Universe.* New York: Harper & Brothers
18. Ekholm N. 1901. On the variations of the climate of the geological and historical past and their causes. *Q. J. R. Meteorol. Soc.* 27:1–61
19. Fleming JR. 1998. *Historical Perspectives*

Page 38

on Climate Change. New York: Oxford Univ. Press
20. Taubenfeld HJ, ed. 1970. *Controlling the Weather: A Study of Law and Regulatory Procedures.* New York: Dunellen
21. Green F. 1977. *A Change in the Weather.* New York: Norton
22. DeLapp RA. 1997. *The politics of weather modification: shifting coalitions.* PhD thesis. Fort Collins: Colorado State Univ.
23. Zikeev NT, Doumani GA. 1967. *Weather Modification in the Soviet Union, 1946–1966; A Selected Annotated Bibliography.* Washington, DC: Libr. Congr., Sci. Technol. Div.
24. Fletcher JO. 1968. *Changing Climate.* Rand Publ. 3933. Santa Monica, CA: Rand Corp.
25. Jt. Publ. Res. Serv. 1963. Review of research and development in cloud physics and weather modification. *Sov.-Block Res. in Geophys., Astron., Space* 83:24512
26. Rusin N, Flit L. 1960. *Man Versus Climate.* Moscow: Peace
27. Schaefer VJ. 1946. The production of ice crystals in a cloud of supercooled water
34. Fogg MJ. 1995. *Terraforming: Engineering Planetary Environments.* Warrendale, PA: Soc. Automot. Eng.
35. McKay CP, Toon OB, Kasting JF. 1991. Making Mars habitable. *Nature* 352:489–96
36. Sagan C. 1961. The planet Venus. *Science* 133:849–58
37. Sagan C. 1973. Planetary engineering on Mars. *Icarus* 20:513–14
38. Hargrove EC, ed. 1986. *Beyond Spaceship Earth*. San Francisco: Sierra Club Books
39. Schneider SH. 1996. Engineering change in global climate. *Forum Appl. Res. Public Policy* 11:92–6
40. Dickinson RE. 1996. Climate engineering: a review of aerosol approaches to changing the global energy balance. *Clim. Change* 33:279–90
41. Budyko MI. 1982. *The Earth's Climate, Past and Future*. New York: Academic
42. MacCracken MC. 1991. *Geoengineering the Climate*. *UCRL-JC-108014*. Livermore, CA: Lawrence Livermore Natl. Lab.

droplets. *Science* 104:457–59
28. Orville HT. 1957. *Final Report of the Advisory Committee on Weather Control*. Washington, DC: US GPO
29. Wexler H. 1958. Modifying weather on a large scale. *Science* 128:1059–63
30. MacDonald GJF. 1968. How to wreck the environment. In *Unless Peace Comes: A Scientific Forecast of New Weapons*, ed. N Calder, pp. 181–205. New York: Viking
31. United Nations. 1976. *Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques.* UN, Treaty Ser. 1108:151
32. Comm. Atmos. Sci. 1962. *The Atmospheric Sciences 1961-1971.* Washington, DC: Natl. Acad. Sci.
33. Comm. Atmos. Sci. 1971. *The Atmospheric Sciences and Man's Needs: Priorities for the Future.* Washington, DC: Natl. Acad. Sci.
43. Teller E, Caldeira K, Canavan G, Govindasamy B, Grossman A, et al. 1999. *Long-Range Weather Prediction And Prevention of Climate Catastrophes: A Status Report. UCRL-JC-135414.* Livermore, CA: Lawerence Livermore Natl. Lab.
43a. Comm. on Satellite Power Syst. 1981. *Electric Power From Orbit: A Critique of a Satellite Power System.* Washington, DC: Natl. Acad. Press
44. Early JT. 1989. Space-based solar shield to offset greenhouse effect. *J. Br. Interplanet. Soc.* 42:567–69
45. Seifritz W. 1989. Mirrors to halt global warming? *Nature* 340:603
46. Lackner K, Wendt CH, Butt DP, Joyce EL, Sharp DH. 1995. Carbon dioxide disposal in carbonate minerals. *Energy* 20:1153–70
47. Geophys. Study Comm. 1977. *Energy*

and Climate. Washington, DC: Natl. Acad. Sci.
48. Dyson FJ. 1977. Can we control the carbon dioxide in the atmosphere? *Energy* 2:287–91
49. Watson AJ. 1997. Volcanic iron, CO_2, ocean productivity and climate. *Nature* 385:587–88
50. Coale KH, Johnson KS, Fitzwater SE, Blain SPG, Stanton TP, Coley TL. 1998. IronEx-I, an in situ iron-enrichment experiment: experimental design, implementation and results. *Deep-Sea Res.* 45:919–45
51. Martin JH, Coale KH, Johnson KS, Fitzwater SE, Gordon RM, et al. 1994. Testing the iron hypothesis in ecosystems of the equatorial Pacific-Ocean. *Nature* 371:123–29
52. Monastersky R. 1995. Iron versus the greenhouse. *Sci. News* 148:220–22
53. Peng TH, Broecker WS. 1991. Dynamic limitations on the Antarctic iron fertilization strategy. *Nature* 349:227–29
54. Kheshgi HS. 1995. Sequestering at-
the climate? *Clim. Change* 33: 309–**21**
61. Schelling TC. 1996. The economic diplomacy of **geoengineering**. *Clim. Change* 33:303–7
62. Schneider SH. 1996. **Geoengineering**: Could or should we do it? *Clim. Change* 33:291–302
63. Simon HA. 1996. *The Sciences of the Artificial*. Cambridge, MA: MIT Press. 3rd ed.
64. Smil V. 1985. *Carbon Nitrogen Sulfur: Human Interference in Grand Biospheric Cycles*. New York: Plenum
65. Tribe L. 1974. Ways not to think about plastic trees: new foundations for enviromental law. *Yale Law J.* 83:1325–27
66. Tribe LH. 1973. Technology assessment and the fourth discontinuity: the limits of instrumental rationality. *South. Calif. Law. Rev.* 46:617–60
67. Singer P. 1990. *Animal Liberation.* New York: Avon
68. Regan T. 1983. *The Case for Animal*

mospheric carbon-dioxide by increasing ocean alkalinity. *Energy* 20:915–22
55. Parson EA, Keith DW. 1998. Fossil fuels without CO_2 emissions. *Science* 282:1053–54
56. Herzog H, Drake E, Adams E. 1997. *CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change. DE-AF22-96PC01257*. Washington, DC: Dep. Energy
57. Archer D, Kheshgi H, Maier-Reimer E. 1997. Multiple timescales for neutralization of fossil fuel CO_2 *Geophys. Res. Lett.* 24:405–8
58. Yudin MI. 1966. The possibilities for influencing large scale atmospheric movements. In *Modern Problems of Climatology*, ed. M Budyko. Ohio: Wright-Patterson AFB, Foreign Technol. Div.
59. Gunderson LH, Holling CS, Light SS, eds. 1995. *Barriers and Bridges to the Renewal of Ecosystems and Institutions*. New York: Columbia Univ. Press
60. Bodansky D. 1996. May we engineer

Rights. Berkeley, CA: Univ. Calif. Press
69. Norton BG. 1987. *Why Preserve Natural Variety?* Princeton, NJ: Princeton Univ. Press
70. Taylor PW. 1986. *Respect for Nature: A Theory of Environmental Ethics*. Princeton, NJ: Princeton Univ. Press
71. Callicott JB. 1989. *In Defense of the Land Ethic: Essays in Enviromental Philosophy*. Albany, NY: SUNY Press
72. Seidel S, Keyes DL. 1983. *Can We Delay a Greenhouse Warming? The Effectiveness and Feasibility of Options to Slow a Build-Up of Carbon Dioxide in the Atmosphere*. Washington, DC: US Environ. Prot. Agency
73. Comm. Atmos. Sci. 1966. *Weather and Climate Modification Problems and Prospects: Final Report of the Panel on Weather and Climate Modification*. Washington, DC: Natl. Acad. Sci.
74. President's Sci. Advis. Comm. 1965. *Restoring the Quality of Our Environment*. Washington, DC: Exec. Off. Pres.

75. Study of Crit. Environ. Probl. 1970. *Man's Impact on the Global Environment; Assessment and Recommendations for Action.* Cambridge, MA: MIT Press
76. Study of Man's Impact Climate. 1971. *Study of Man's Impact on Climate: Inadvertant Climate Modification.* Cambridge, MA: MIT Press
77. Natl. Res. Counc. 1979. *Carbon Dioxide and Climate: A Scientific Assessment*. Washington, DC: Natl. Acad. Press
78. Carbon Dioxide Assess. Comm. 1983. *Changing Climate*. Washington, DC: Natl. Acad. Press
79. Off. Technol. Assess. 1991. *Changing By Degrees: Steps To Reduce Greenhouse Gases*. Washington, DC: US Congr.
80. Lashof DA, Tirpak DA. 1990. *Policy Options For Stabilizing Global Climate*. New York: Hemisphere
81. Intergov. Panel Climate Change. 1991. *Climate Change: The IPCC Response Strategies*. Washington, DC: Island Press
82. Bruce JP, Lee H, ed. 1996. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Cambridge, UK: Cambridge Univ. Press