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Weather and Climate Engineering

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Abstract

In this chapter I present an overview of the concepts and status of the science of weather and climate engineering. I begin by discussing the concepts of seeding clouds through glaciogenic and hygroscopic seeding. I review the status of research on these concepts for increasing rainfall, decreasing hail damage, and reducing hurricane intensity. Thereafter I present an overview of the concepts for climate engineering to counter greenhouse warming. These include seeding in the stratosphere with sulfate-producing gases and aerosols, and carbonaceous aerosols. I also consider hygroscopic seeding of marine stratocumulus boundary layer clouds to enhance their albedo and cause a cooling effect. Also considered is seeding mid-level stratus clouds to enhance their albedo during the day and increasing outgoing longwave radiation during the night time. Cirrus clouds present a major obstacle to climate modification owing to their widespread global coverage and their tendency to warm the surface, thus reinforcing greenhouse warming. Speculations on the seeding of carbonaceous aerosols to clear cirrus through a semi-direct effect are presented. Most of the proposed concepts require a great deal of research to quantify their impacts and potential adverse consequences.

I include a long list of the reasons as to why we should *not* apply climate engineering. Despite these, I anticipate that if we find ourselves in a true climate crisis, politicians will call for climate engineering measures in an attempt to alter adverse climate trends. If this should ever be the case, let us be sure that we do so with the most advanced level of knowledge of the climate system and the full consequences of our actions.

Introduction

I have been tasked with the job of providing a position paper on weather modification and geoengineering. I have titled this paper "Weather and Climate Engineering" and, in doing so, have discarded the normally used term "weather modification" so that it relates better to climate engineering. Moreover, I have chosen the term “climate engineering” as I am going to focus mainly on hypotheses for engineering changes in the Earth’s albedo or longwave radiation rather than discuss policies for reducing carbon emissions, sequestration of carbon, and so forth. At the outset I wish to state that this is written from the perspective of a scientist who is naturally skeptical about the many claims of how humans can influence weather and climate. This philosophy of what I will call “healthy skepticism” grew out of my graduate training in weather modification research, where there were many claims of great success in modifying the weather. After over fifty years of research, there is still no strong physical and statistical evidence that these early claims were ever realized.

I have carried that skepticism into the area of climate change where there seems to be a consensus among the scientific community (IPCC 2007) that human production of CO_2 is causing a global warming trend. I do not deny that the evidence is very strong that we are in a period of global climate warming and that adding CO_2 to the atmosphere will contribute to warming. However, I remain skeptical that current global warming trends are due solely to human causes and that other causes of natural climate variability are not the major contributing factors. This perspective on weather modification and climate change is discussed by Cotton and Pielke (2007).

Thus it is with this philosophical view that I venture into the domain of weather and climate engineering. I do so in spite of my belief that we should not be further “mucking” up our environment but also recognize that we may at some point in the future have to resort to modifying weather and climate in order to provide sufficient water resources and a climate capable of sustaining the population of humans on this planet.

Weather Engineering

Over the last fifty years, weather engineering or weather modification has mainly focused on cloud seeding. There have been a few hypotheses advanced to modify weather or regional climate that do not involve cloud seeding: Anthes (1984) hypothesized that trees and crops could be planted in mesoscale patches to provide optimum forcing for regional weather circulations and convective precipitation; Black and Tarmy (1963) suggested using waste asphalt to make strips of low-albedo surfaces to enhance mesoscale circulations and rainfall. By and large, however, most activity in weather engineering has been associated with cloud seeding.

During this time, deliberate cloud seeding has been pursued, with the goal of increasing precipitation through the injection of specific types of particles into clouds. Efforts to understand the processes involved have led to a significant body of knowledge about clouds and about the effects of the seeding aerosol. A number of projects focused on the statistical evaluation of whether a seeding effect can be distinguished in the presence of considerable “natural variability.”

In this chapter, I review briefly the fundamental concepts of cloud seeding. It is not my intent to provide a complete assessment of the current status of cloud seeding research. For this, I direct the reader to more comprehensive weather modification assessments in NRC (2003), Cotton and Pielke (2007), Silverman (2001, 2003), Garstang et al. (2005), and Levin and Cotton (2008).

Deliberate cloud seeding experiments can be divided into two broad categories: *glaciogenic* and *hygroscopic* seeding. Glaciogenic seeding occurs when ice-producing materials (e.g., dry ice or solid CO_2, silver iodide, liquid propane) are injected into a supercooled cloud to stimulate precipitation via the ice particle mechanism. The underlying hypothesis for glaciogenic seeding is that there is commonly a deficiency of natural ice nuclei and therefore insufficient ice particles for the cloud to produce precipitation as efficiently as it would in the absence of seeding.

Hygroscopic seeding, by contrast, was generally used in the past to enhance rain from warm clouds (for a review of early hygroscopic seeding research, see Cotton 1982). More recently, however, it has been applied to mixed-phase clouds as well. The goal of hygroscopic seeding is to increase the concentration of *collector drops* that can grow efficiently into raindrops by collecting smaller droplets and by enhancing the formation of frozen raindrops and graupel particles. This is done by injecting into a cloud (generally at cloud base) large or giant hygroscopic particles (e.g., salt powders) that can grow rapidly through the condensation of water vapor to produce collector drops.

Glaciogenic Cloud Seeding

Glaciogenic cloud seeding can be subdivided into *static cloud* and *dynamic cloud* seeding. Static cloud seeding refers to the use of glaciogenic materials to modify the microstructures of supercooled clouds and precipitation. Many hundreds of such experiments have been conducted over the past fifty years. Some have been operational cloud seeding experiments (many of which are still being carried out around the world), which rarely provide sufficient information to form a decision as to whether or not they have modified either clouds or precipitation. Others have been well-designed scientific experiments that have yielded extensive measurements and modeling studies to permit an assessment of whether the artificial seeding modified cloud structures and, if the seeding was randomized, what effects the seeding had on precipitation. Although there still is some debate about what constitutes firm "proof" (see NRC 2003; Garstang et al. 2005) that seeding affects precipitation, it is generally required that *both* strong physical evidence of appropriate modifications to cloud structures and highly significant statistical evidence be obtained.

Glaciogenic Seeding of Cumulus Clouds

The static seeding concept has been applied to supercooled cumulus clouds and tested in a variety of regions. Two landmark experiments (Israeli I and Israeli II), carried out in Israel, have been described in peer-reviewed literature. These experiments were carried out by researchers at the Hebrew University of Jerusalem, hereafter the experimenters. These two experiments were the foundation for the general view that under appropriate conditions, cloud seeding increases precipitation (e.g., NRC 1973; Sax et al. 1975; Tukey et al. 1978a, b; Simpson 1979; Dennis 1980; Mason 1980, 1982; Kerr 1982; Silverman 1986; Braham 1986; Cotton 1986a, b; Cotton and Pielke 1992; 2007; Young 1993).

Nonetheless, a reanalysis of those experiments by Rangno and Hobbs (1993) suggests that the appearance of seeding-caused increases in rainfall in the Israel I experiment was due to "lucky draws" or a Type I statistical error. Furthermore, they argue that during Israel II naturally heavy rainfall over a wide region encompassing the north target area gave the appearance that seeding caused increases in rainfall over the north target area. At the same time, lower natural rainfall in the region encompassing the south target area gave the appearance that seeding decreased rainfall over that target area. This speculation, however, could not explain the positive effect when the north target area was evaluated against the north upwind control area. Details of this controversy can be found in the March 1997 issue of the *Journal of Applied Meteorology* (Rosenfeld 1997; Rangno and Hobbs 1997a; Dennis and Orville 1997; Rangno and Hobbs 1997b; Woodley 1997; Rangno and Hobbs 1997c; Ben-Zvi 1997; Rangno and Hobbs 1997d). Some of these responses clarified issues; others left many questions unanswered.

Another noteworthy experiment was carried out in the high plains of the United States (High Plains Experiment or HIPLEX-1; Smith et al. 1984). Analysis of HIPLEX-1 revealed the important result that after just five minutes, there was no statistically significant difference in the precipitation between seeded and non-seeded clouds (Mielke et al. 1984). Cooper and Lawson (1984) found that while high ice crystal concentrations were produced in the clouds by seeding, the cloud droplet region, where the crystals formed, evaporated too quickly for the incipient artificially produced ice crystals to grow to appreciable sizes. Instead, they formed low-density, unrimed aggregates that had the water equivalent of only drizzle drops, which were too small to reach the ground before evaporating. Schemenauer and Tsonis (1985) affirmed the findings of Cooper and Lawson in a reanalysis of the HIPLEX data, emphasizing their own earlier findings (Isaac et al. 1982) that cloud lifetimes were too short in the HIPLEX domain for seeding to have been effective in the clouds targeted for seeding (i.e., those with tops warmer than –12ºC). Although the experiment failed to demonstrate statistically all the hypothesized steps, the problems could be traced to the physical short lifetimes of the clouds (Cooper and Lawson 1984; Schemenauer and Tsonis 1985).

Glaciogenic Seeding Winter Orographic Clouds

The static mode of cloud seeding has also been applied to orographic clouds. Precipitation enhancement of orographic clouds by cloud seeding has several advantages over cumulus clouds. The clouds are persistent features that produce precipitation even in the absence of large-scale meteorological disturbances. Much of the precipitation is spatially confined to high mountainous regions, thus making it easier to set up dense ground-based seeding and observational networks. Moreover, the “natural variability” of orographic clouds is less than cumulus clouds, thus making it easier to identify a “cause and effect.”

The landmark randomized cloud seeding experiments conducted at Climax, near Fremont Pass, Colorado (referred to as *Climax I* and *Climax II*), reported by Grant and Mielke, suggested increases in precipitation of 50% and more on favorable days (e.g., Grant and Mielke 1967; Mielke et al. 1970, 1971). These results were widely viewed as demonstrating the efficacy of cloud seeding (e.g., NRC 1973; Sax et al. 1975; Tukey et al. 1978a, b), even by those most skeptical of cloud seeding claims (e.g., Mason 1980, 1982).

Nonetheless, Hobbs and Rangno (1979; Rangno and Hobbs 1987, 1993) questioned both the randomization techniques and quality of data collected during those experiments and concluded that the Climax II experiment failed to confirm that precipitation can be increased by cloud seeding in the Colorado Rockies. Even so, in their reanalysis, Rangno and Hobbs (1993) did show that precipitation increased by about 10% in the combined Climax I and II experiments.

Two other randomized orographic cloud seeding experiments, the Lake Almanor Experiment (Mooney and Lunn 1969) and the Bridger Range Experiment (BRE) as reported by Super and Heimbach (1983) and Super (1986), suggested positive results. These particular experiments, however, used high elevation AgI generators, which increase the chance that the AgI plumes get into the supercooled clouds. Moreover, both experiments provided physical measurements that support the statistical results (Super and Heimbach 1983, 1988).

Finally, Ryan and King (1997) reviewed over 14 cloud seeding experiments covering much of southeastern, western, and central Australia as well as the island of Tasmania. They concluded that static seeding over the plains of Australia is not effective. They argue that for orographic stratiform clouds, there is strong statistical evidence that cloud seeding increased rainfall, perhaps by as much as 30% over Tasmania, when cloud top temperatures are between –10° and –12°C in southwesterly airflow. The evidence that cloud seeding had similar effects in orographic clouds over the mainland of southeastern Australia is much weaker. Note that the Tasmanian experiment had both strong statistical and physical measurement components and thus meets or at least comes close to meeting the NRC (2003) criteria for scientific “proof.” Benefit/cost analysis of the Tasmanian experiments suggests that seeding has a gain of about 13/1. This is viewed as a real gain to hydrologic energy production.

In summary, the "static" mode of cloud seeding has been shown to cause the expected alterations in cloud microstructure, including increased concentrations of ice crystals, reductions of supercooled liquid water content, and more rapid production of precipitation elements in both cumuli (Isaac et al. 1982; Cooper and Lawson 1984) and orographic clouds (Reynolds 1988; Super and Boe 1988; Super et al. 1988; Super and Heimbach 1988; Reynolds and Dennis 1986). The documentation of increases in precipitation on the ground due to static seeding of cumuli, however, has been far more elusive with the Israeli experiment (Gagin and Neumann 1981), providing the strongest evidence that static seeding of cold-based, continental cumuli can cause significant increases of precipitation on the ground. The evidence that orographic clouds can cause significant increases in snowpack is far more compelling, particularly in the more continental and cold-based orographic clouds (Mielke et al. 1981; Super and Heimbach 1988).

The most challenging obstacles to evaluating cloud seeding experiments to enhance precipitation are perhaps the inherent "natural variability" of precipitation in space and time as well as the inability to increase precipitation amounts to better than ~10%. The latter puts great demands on measuring accuracy and the duration of the experiments. The fact that the evidence is stronger that glaciogenic seeding increases precipitation in orographic clouds than cumulus clouds is probably a consequence of their lower "natural variability." This is also consistent with the findings of Levin and Cotton (2008), who show that the strongest evidence that aerosol pollution reduces precipitation is from orographic clouds. Again, the fact that orographic clouds exhibit a lower level of "natural variability" may be a major contributing factor.

Dynamic Glaciogenic Seeding

Thus far we have considered only static seeding, in which the principal thrust is to modify the microstructures of clouds generally for the purpose of enhancing precipitation. There is, however, another glaciogenic seeding hypothesis in which the cloud-scale dynamics of a cloud is enhanced by stimulating buoyancy and upward motions of air. This is referred to as *dynamic cloud seeding*. In principal, this can be done by glaciating convective clouds so that large quantities of latent heat are released by the freezing of copious liquid water to invigorate updrafts in the cloud. This can be particularly effective if, prior to seeding, the tops of the clouds are restricted by a shallow stable layer produced by a temperature inversion. In this case, the sudden release of a large quantity of latent heat might provide enough buoyancy to push the top of the cloud through the stable layer and into a region where the air is naturally unstable. The cloud might then rise to much greater heights than it would have done naturally. To some extent the distinction between static seeding and dynamic seeding is rather artificial. As has been shown in recent modeling studies of the effects of aerosol pollution on stratocumuli, small cumuli, and cumulonimbi, any modification of precipitation from these clouds contributes to nonlinear dynamical responses in the clouds and cloud systems (Levin and Cotton 2008).

In a series of randomized experiments carried out in Florida in 1968 and between 1970–1973 (called the Florida Area Cumulus Experiment or FACE), it was found that precipitation (measured by radar) from isolated cumulus clouds ~5 km in diameter, which were artificially seeded to induce explosive growth, was about twice that of the unseeded control clouds (e.g., Simpson and Woodley 1975; Woodley et al. 1982). The seeded clouds rained more than the control clouds since they were bigger and lasted longer, rather than because their rainfall rates were significantly greater.

In FACE II, the attempt was made to confirm and replicate the results of FACE I by going the additional step of specifying the manner in which clouds would respond to seeding based on what was understood to have been the response in FACE I. Although there were several suggestions of seeding effects on some clouds and some days (e.g., Woodley et al. 1983), the overall experiment officially failed to confirm the results of FACE I (Flueck et al. 1981; Nickerson 1979, 1981). In essence, the experiment succumbed to the high "natural variability" of these storms.

In recent years the dynamic seeding strategy has been applied in Thailand and West Texas. Results from exploratory dynamic seeding experiments over West Texas have been reported by Rosenfeld and Woodley (1989, 1993). Analysis of the seeding of 183 convective cells suggests that seeding increased the maximum height of the clouds by 7%, the areas of the cells by 43%, the durations by 36%, and the rain volumes of the cells by 130%. The results are encouraging, but such small increases in vertical development of the clouds are hardly consistent with earlier exploratory seeding experiments.

As a result of their experience in Texas, Rosenfeld and Woodley (1993) proposed an altered conceptual model of dynamic seeding in which explosive vertical development of seeded clouds is not emphasized. As pointed out by Silverman (2001), however, application of the revised hypothesis in Thailand (Woodley et al. 2003a, b) indicated rainfall enhancement, but the results did not reach statistical significance. Moreover, the enhanced downdraft presumably produced by it did not appear to be delayed (Woodley et al. 1999b).

In summary, the concept of dynamic seeding is a physically plausible hypothesis that offers the opportunity to increase rainfall by much larger amounts than simply enhancing the precipitation efficiency of a cloud. It is a much more complex hypothesis, however, requiring greater quantitative understanding of the behavior of cumulus clouds and their interaction with each other, with the boundary layer, and with larger-scale weather systems.

Hygroscopic Cloud Seeding

Hygroscopic seeding was mainly used in the past in warm clouds, where no ice is present. More recently, this type of seeding method has been tried in mixed-phase clouds. The aim in seeding warm clouds is to enhance drop growth by coalescence, thus improving the efficiency of rainfall formation. However, seeding mixed-phase clouds seems to affect both drop growth and ice formation, probably through the efficient formation of graupel particles. As the modeling studies of Cotton (1972), Murray and Koenig (1972), and Scott and Hobbs (1977) suggest, a cloud composed of larger supercooled drops is likely to glaciate much faster than one composed primarily of small drops. Appropriately sized salt particles, water droplets from sprays of either water or saline solution (Bowen 1952; Biswas and Dennis 1971; Cotton 1982; Murty et al. 2000; Silverman and Sukarnjanasat 2000), and hygroscopic flares (Mather et al. 1997; WMO 2000) have been used for seeding. Recent enthusiasm for the concept was motivated by Mather's (1991) study, which demonstrated the effects of paper-mill effluent on precipitation. Statistical results, observations, and modeling results provided some evidence that precipitation may be enhanced under certain conditions and with optimal seed drop size spectra (Farley and Chen 1975; Rokicki and Young 1978; Young 1996; Reisin et al. 1996; Yin et al. 2000a, b). Seeding experiments using hygroscopic flare particles provided statistical support for rainfall increases due to seeding based on single cloud analyses (Mather et al. 1997; Bigg 1997; WMO 2000; Silverman 2003). Model simulations suggest that the increase in rainfall amounts stems from the increase in graupel numbers and masses, which are generated by the increased concentrations of large drops (Yin et al. 2000a, b). Such increases could generate more rain, but it is not clear how these procedures can affect the clouds for such a length of time, as some of the measurements suggest (e.g., Silverman 2003).

In both South Africa (Mather et al. 1997) and Mexico (WMO 2000), hygroscopic flares have been applied to mixed-phase convective cloud systems in limited physical and statistical experiments. Aircraft microphysical measurements were made to verify some of the processes involved. Radar-measured 30 dBZ volumes, produced by the convective complexes, were tracked by automated software, and various storm and track properties were calculated. These two sets of experiments produced remarkably similar results in terms of the difference in radar-estimated rainfall between the seeded and non-seeded groups. The South African data have been reevaluated independently by Bigg (1997) and Silverman (2000); both concluded that there is statistically significant evidence of an increase in *radar-estimated* rainfall from seeded convective cloud systems.

Mather et al. (1997), Bigg (1997), and Silverman (2000) all allude to apparent dynamic effects of seeding clouds, manifest in the seeded cloud systems, being longer-lived. It was speculated that the relation between (a) the amount of precipitation (negative buoyancy due to the weight of condensed water) and evaporation, (b) the characteristics of the downdraft that is generated, and (c) the downdraft and the storm organization, evolution, and lifetime determines the dynamic effect of seeding on rainfall. Another factor not mentioned is the possible consequences of altered raindrop size distributions. If seeding shifts the raindrop size distribution to smaller raindrops, then greater sub-cloud evaporation would ensue, which would alter cold-pool dynamic effects. If seeding shifts the raindrop spectrum to larger drops, the opposite response would be expected (Yin et al. 2001).

It appears that continental convective storms are remarkably sensitive to changes in the cloud condensation nuclei (CCN) ingested at cloud base. For example, both the South African and Mexican experiments with hygroscopic flares show very strong signals in terms of increased storm lifetime in seeded storms, increases in reflectivity aloft, and increases in storm densities. Thus, these hygroscopic flare seeding experiments suggest that it is possible, under appropriate conditions, to produce large differences in cloud properties by injection of hygroscopic particles into cloud bases.

In its assessment of weather modification research, the NRC (2003) concluded that the South African and Mexican experiments have demonstrated responses in clouds to treatment in accordance with understanding of the chain of physical reactions leading to precipitation. However, since the analyzed statistical results are for radar-defined floating targets, they still do not prove that rainfall can be increased by hygroscopic seeding on the ground for specific watersheds. Moreover, since seeding may alter the size spectrum of raindrops, which alters the radar return, uncertainties exist in the evaluation of actual rain amounts for seeded versus non-seeded floating targets. Finally, since the main response to seeding found in the South African, Mexican, and Thailand experiments is delayed in time for as much as 1 to 6 hours, following the cessation of seeding, we lack a clear understanding of the actual processes that could lead to such a physical response.

Thus while the results of the hygroscopic seeding experiments are quite promising, they still do not constitute a "proof" that hygroscopic seeding can enhance rainfall on the ground over an extended area. The areas affected by cloud seeding have not yet been characterized. In after-the-fact analyses, several rain enhancement projects have reported evidence for physical effects outside the area or timing originally designated as the target, or beyond the time interval when seeding effects were anticipated. For example, in recent large particle hygroscopic and glaciogenic seeding trials involving warm-base convective clouds in Thailand and Texas, increases in rain were reported 3 to 12 hours after seeding was conducted (Woodley et al. 1999), well beyond the time that direct effects of seeding were expected and possibly outside the target area.

Other Cloud Seeding Applications

Cloud seeding strategies have also been applied to hail suppression and reduction in hurricane intensity. Following many years of research, scientific field confirmation of the concepts of hail suppression has been largely unsuccessful (Atlas 1977; Federer et al. 1986). Only long-term statistical analyses of non-randomized, operational programs have provided convincing evidence, suggesting that seeding can significantly reduce hail frequency (Mesinger and Mesinger 1992; Smith et al. 1997; Eklund et al. 1999; Rudolf et al. 1994; Dessens 1998). An advantage of evaluating an operational program is that often one can work with long-period records (e.g., forty years in Yugoslavia), whereas randomized research programs cannot typically get funding for more than five years or so. The disadvantage is that one cannot totally eliminate concerns about "natural variability" in the climate (see comments in NRC 2003).

Likewise, attempts to modify hurricanes (Simpson et al. 1963; Simpson and Malkus 1964; Gentry 1974; Sheets 1981) failed to confirm the proposed hypotheses. In a sense, Stormfury succumbed to the very large "natural variability" of hurricanes, including a period of very low hurricane frequency from the mid-1960s to the mid-1980s (Sheets 1981). As a result, interest and government funding for hurricane modification plummeted. Although there have been recent simplified modeling studies that suggest that seeding hurricanes with pollution-sized aerosols may weaken storm intensity (Rosenfeld et al. 2007; Cotton et al. 2007), these concepts need to be developed more quantitatively.

Implications of Cloud Seeding Research to Climate Engineering

The scientific community has established a set of criteria to determine when there is "proof" that seeding has enhanced precipitation (NRC 2003; Garstang et al. 2005): *both* strong physical evidence of appropriate modifications to cloud structures and highly significant statistical evidence are required. Likewise, for firm "proof" that climate engineering is affecting climate, or even that CO_2 is modifying climate, both strong physical evidence of appropriate modifications to climate and significant statistical evidence should be required.

A lesson from evaluating cloud seeding experiments is that "natural variability" of clouds and precipitation can be quite large and can thus inhibit conclusive evaluation of even the best-designed statistical experiments. The same can be said for evaluating the effects of climate engineering or whether human-produced greenhouse gases are altering climate. If the signal is not strong, then evaluating whether human activity has produced some observed effect (cause and effect) requires much longer time records than is available for most, if not all, data sets. To do so, we have to resort to "proxy" data sets, which results in uncertainties in calibrations, inconsistencies between older data estimates and more recent measurements, large noise in the data, and inadequate coverage of sampling of the selected control variables. Thus, at present, we do not have an adequate measure of the "natural variability" of climate, which makes venturing into climate engineering hazardous indeed.

Climate Engineering

The climate system is far more complicated than many scientists lead us to believe. There is considerable evidence that the planet Earth is warming. Furthermore, the concentrations of CO_2 are also increasing at alarming rates. The question is: Are these cause-and-effects or is the planet warming for other reasons? The so-called "hockey stick" paper of Mann et al. (1998) provides the strongest evidence that the current period of global warming is unprecedented over the last 1000 years or so. Their analysis is based on proxy data that includes ice cores, tree rings, marine sediments, and historical sources from Europe and Asia. These data are therefore evidence for warming in the northern hemisphere; proxy and historical data for the southern hemisphere are very sparse. This paper, however, has been criticized by a number of scientists (e.g., McIntyre and McKitrick 2003; von Storch et al. 2006) as having major problems in the statistical treatment of the data. The National Research Council (2006) reported on an independent evaluation of Mann et al.'s conclusion and on the use of proxy data, and concluded that the last few decades of the 20th century were warmer than any period in the last 400 years. They stated that the conclusion reached by Mann et al.—that it was warmer than any period in the last 1000 years—is plausible but that there is less confidence that the warming was unprecedented for periods prior to 1600, owing to fewer proxies at fewer locations available prior to 1600. They noted that none of the reconstructions indicated that it was warmer during the Medieval Climate Optimum than during the end of the 20th century. That there were regions of the northern hemisphere that were warmer during the Medieval Climate Optimum can be seen from reconstructions of surface temperatures for the Sargasso Sea (Robinson et al. 2007). These data suggest that the warming period that we are experiencing has been going on for over 300 years (i.e., since the end of the Little Ice Age) and that the Medieval Climate Optimum period 1000 years ago was much warmer. There is also circumstantial evidence that the climate in Greenland, for example, was much warmer during the Medieval Climate Optimum period as the glaciers were much reduced in coverage and the seas were more open to navigation. Considering the scarcity of data, I find it difficult to conclude that we know enough about the "natural variability" of climate over the last 1000 years to state that this recent period of warming is unprecedented.

CO_2 is clearly a major absorber of longwave radiation and therefore contributes to so-called greenhouse gases. We need, however, to keep in mind that CO_2 is not the major greenhouse gas; water vapor has that distinction. Thus, much of the greenhouse warming in models is due to feedbacks that involve higher concentrations of water vapor in the atmosphere, which then contributes to most of the greenhouse warming. Clouds are very important absorbers of longwave radiation as well as the albedo of our planet. Low clouds tend to enhance the Earth's albedo (a cooling affect) while having little influence on the longwave radiation budget because their temperatures are close to that of the Earth's surface. On the other hand, high clouds tend to absorb more longwave radiation while (with the exception of optically thick tropical anvil-cirrus clouds) reflecting small amounts of shortwave radiation; therefore they serve as greenhouse warmers. Because models depend on rather crude parameterizations of clouds, it is still uncertain how clouds respond to a warming planet and to the enhanced water vapor content of the atmosphere. Are there more high clouds versus low clouds in a warming planet? How does cloud variability change with latitude? Increased cloud cover at high latitudes contributes to a warming trend in the Arctic since the annually averaged surface energy budget at high latitudes is dominated by longwave radiation.

While greenhouse gases, especially water vapor, are a major contributor to the habitability of planet Earth, is the variability of these gases the dominant contributor to climate change?

What are some of the other competing processes that change the forcing of our climate system? These are reviewed in Cotton and Pielke (2007) and include the following:

- changes in solar luminosity and orbital parameters,
- changes in surface properties,
- natural and human-induced changes in aerosols and dust,
- differential temporal responses to external forcing by the atmosphere and oceans.

Changes in Earth orbital parameters, the so-called Milankovitch cycle (Imbrie and Imbrie 1979; Berger 1982), are believed to be responsible for the onset of ice ages. It is unable, however, to explain the current warming trend, as it predicts we will be moving into an ice age in the next 5000 years. Although there is evidence of a small variation in the sun's irradiance, the amount of variability is too small to account for recent climate variations, let alone any over the last 1000 years. While many studies have suggested statistical correlations between varying solar parameters and the Earth's climate (i.e., Svensmark and Friis-Christensen 1997), the physical causes of those correlations are for the most part not well founded (Sun and Bradley 2002). Nonetheless, this does not mean that some unknown amplification process related to solar parameters could be contributing to the current warming trend. It remains as part of the uncertainty in climate prediction.

Variations in land-surface properties affect the planetary albedo and alter the surface energy budget such that the Bowen ratio can be changed. Human activity contributes to changes in surface properties through agricultural land use and urbanization. Moreover, changes in land use and vegetation respond to climate changes in a nonlinear way, thus altering both the planetary albedo and the surface energy budget. Although changes in land-surface properties are a significant contributor to the planetary energy budget, they do not probably rank as high as greenhouse warming (IPCC 2007). Nonetheless, the IPCC's estimates are based only on changes in albedo and do not include changes in sensible and latent heat fluxes which should make changes in global climate by land-use changes larger than estimated by IPCC.

Cotton and Pielke (2007) devoted an entire chapter to human-induced changes in aerosols. The chapter considers both the direct and semi-direct effects of aerosols and dust as well as indirect effects that alter the Earth's albedo and hydrologic budget through alterations in cloud properties. Large uncertainties exist in estimating the consequences of aerosols on climate largely because of the fact that a major contributor is related to cloud processes, which are poorly represented in GCMs. Nonetheless, it is generally believed that human-induced changes in aerosols contribute to a net cooling in the climate system, which offsets greenhouse warming by roughly one-third that of greenhouse gas warming (IPCC 2007), or to what is sometimes referred to as "global dimming." Some GCM simulations of greenhouse warming and direct and indirect aerosol effects (Liepert et al. 2004) show that the indirect and direct cooling effects of aerosols reduce surface latent and sensible heat transfer and, as a result, act to dry the atmosphere and thereby substantially weaken greenhouse gas warming. Since greenhouse warming causes a moistening of the atmosphere, and aerosol direct and indirect cooling counteracts that, the potential influence of aerosols on global climate could be far more significant than previously thought.

A major "wild card" in the climate system is naturally produced aerosols and specifically aerosols in the lower stratosphere induced by volcanic activity. Until recently, I had thought that volcanic activity was purely random. A series of papers by Reid Bryson and colleagues (Bryson and Goodman 1980a, b; Bryson 1982, 1989; Goodman 1984) suggests otherwise. These papers suggest that volcanic activity is modulated by the Sun–Moon–Earth tidal variations. Under this scenario, periods of global warming, such as we are now experiencing, can be attributed to periods of very low volcanic activity as seen between 1920 and 1940 (Robock 1979) and the Medieval Climate Optimum period. Periods of extensive cooling, like the Little Ice Age, were periods of maximum alignment of the Sun–Moon–Earth tidal forcing, which contributed to very active episodes of volcanic activity and global cooling. The consequence of this is that forecasts of global greenhouse gas warming are at the mercy of climate variability due to volcanic activity. Periods of greater than normal volcanic activity could completely override or mask the forcing by greenhouse gases. Is it possible that the current warming period is due to a period of below normal volcanic activity?

Finally, the atmosphere and ocean have very different timescales of response to external forcing: the atmospheric timescale is on the order of months, the ocean mixed layer is on the order of ten years, and the deep ocean is 100 years.

Thus, the current climate is being influenced by changes in external forcing that occurred as long as 100 years ago. This mismatch between ocean and atmosphere response to external forcing is a major contributor to "natural variability" of the climate system.

Based on this overview of cloud seeding, I will now address climate engineering. I will only focus on climate engineering as it pertains to engineering changes in global albedo and top-of-atmosphere longwave radiation emission by aerosols and cloud modification. I will not go into the broader context of geoengineering, which includes such things as capturing and disposing of CO_2 from flue gas streams, increasing net CO_2 uptake in the terrestrial biosphere, increasing net CO_2 uptake in the oceans, carbon sequestration, alternate energies, or even changing the albedo of oceans and land surfaces.

Emulating Volcanoes

Volcanoes are a major "wild card" in the climate system. A major volcanic eruption distributes large quantities of dust and debris into the upper troposphere and lower stratosphere. More importantly, it introduces large quantities of SO_2 into the lower stratosphere where it is subjected to slow gas-to-particle production, particularly the formation of sulfuric acid drops. These highly soluble drops scatter solar radiation, thus reducing the amount of sunlight that reaches the surface. A single major eruption can produce a reduction in solar radiation that can last for anything up to two years and can result in residual heat loss in the ocean-mixed layer for as long as ten years.

The idea of introducing sulfate aerosols into the stratosphere dates back to Budyko (1974) and Dyson and Marland (1979), and has received recent prominence by the Nobel Laureate, Paul Crutzen (2006). The idea is to burn S_2 or H_2S carried into the stratosphere by balloons, artillery guns, or rockets to produce SO_2. Crutzen suggests that to enhance residence time, and thereby minimize the mass required, the gases should be introduced in the upward stratospheric circulation branch in the tropics where slow gas-to-particle conversion can take place. He estimates that 1.9 Tg S would be required to offset 1.4 W m^{-2} warming by CO_2, and that this can be achieved by continuous deployment of about 1–2 Tg S per year for a total cost of $25–50 billion per year. To compensate for a doubling of CO_2 (estimated 4 W m^{-2} warming), Crutzen estimates that 5.4 Tg S per year are needed with corresponding cost increases. As with volcanoes, we can expect the sky to be whitened and that red sunsets and sunrises will prevail. One adverse consequence of SO_2 seeding the stratosphere is that stratospheric ozone would be reduced. Crutzen noted that El Chichón introduced 3–5 Tg S in the stratosphere and reduced ozone by 16% at 20 km altitude, whereas Mt. Pinatubo introduced 10 Tg S, which contributed to a 2.5% reduction in column ozone loss. I imagine that this could translate into rates of increased incidence of skin cancer by higher UV radiation amounts.

Another option noted by Crutzen would be to release soot particles in the lower stratosphere by burning fossil fuels. Like the nuclear winter hypothesis (see review by Cotton and Pielke 2007), the resulting soot particles would absorb solar radiation, which would deplete solar radiation reaching the surface but also warm the stratosphere. This warming could have undesirable consequences in terms of changes in stratospheric circulations and ozone depletion. It would be less costly to deliver as only 1.7% of the mass of sulfur would be needed to produce the same cooling effect.

Rather than manufacture scattering or absorbing aerosols *in situ*, it has also been suggested that mirrors can be introduced in space. The National Academy of Sciences proposed deployment of something like 55,000 mirrors with a surface area of 100 km^2 into the Earth's orbit (NAS 1992). These mirrors would deplete about 2% of solar radiation, but each mirror would also create a shadow in the shape of an eclipse. A greater number of smaller mirrors have also been proposed, but these would create a flickering of sunlight. In addition to the installation costs, removing the mirrors, if undesirable responses developed, would be difficult and expensive.

Early (1989) has also proposed the introduction of a solar shield at the Sun–Earth Lagrange point (1.5×10^6 km from Earth). This could reflect 2% of solar radiation reaching Earth, but would cost in the trillion dollar range to install. In the event of adverse responses, removal would be easier and less costly than a large number of mirrors.

When we consider such options, we must keep in mind that altering solar radiation is quite different from changing longwave radiation. CO_2 traps longwave radiation both day and night, whereas reducing sunlight affects only daytime radiation and, on the annual average, most strongly in equatorial regions and in summer seasons at high latitudes (Govindasamy and Cadeira 2000). Govindasamy and Cadeira performed GCM simulations that emulated the above proposed changes in solar radiation by lowering the solar constant by 1.8%, which would offset a doubling of the CO_2 scenario. As anticipated, the climate-engineered simulations produced the most cooling in the tropics but reduced the amplitude of the diurnal cycle over land by only 0.1K. Govindasamy and Cadeira found that the amplitude of the seasonal cycle was greater in the climate-engineered simulation than in the double CO_2 simulation at high latitudes because there was more sea ice in the climate-engineered simulation. Sea ice tends to insulate the warmer underlying waters from the overlying air, resulting in colder winters and amplification of the seasonal cycle. Little change in the model's hydrological cycle was noted in either their double CO_2 simulation or the climate-engineered simulation.

Back to Cloud Seeding

Purposeful cloud seeding has been mainly designed to increase precipitation or modify storms. Could cloud seeding strategies, however, be designed either to increase cloud albedo or the amount of longwave radiation escaping to space? As reviewed by Levin and Cotton (2008), there is plenty of evidence to show that pollution aerosols are inadvertently modifying cloud radiative properties and precipitation. One problem in implementation is that any aerosols introduced into the troposphere, particularly the lower troposphere, must be done almost continuously as the residence times are so short, generally on the order of a few days or at most a few weeks. This limitation makes these options much more costly than those proposed for the stratosphere or space unless this is done on the basis of business as usual; that is, these changes would be associated with normal industrial operations, ship operations, or aircraft operations. One motivation for Crutzen's (2006) paper is that as we become successful in cleaning up industrial aerosol pollution, which current estimates suggest causes a significant cooling effect that offsets greenhouse warming, the amplitude of global warming will become greater. Moreover, much of the estimated cooling by aerosol pollution may be a result of indirect effects associated with clouds. Hence, we should consider how to pollute clouds without producing disastrous adverse consequences. Admittedly this may be impossible; however, let us speculate how cloud seeding could be applied to climate engineering.

More Ship Tracks!

The strongest evidence that we have that pollution aerosols increase cloud albedo comes from ship tracks (Figure 17.1). In fact, Porch et al. (1990) referred to them as the *Rosetta Stone* connecting changes in aerosols over the oceans and cloud albedo effects on climate.

Measurements show that ship tracks contain higher droplet concentrations, smaller droplet sizes, and higher liquid water contents than surrounding clouds (Radke et al. 1989). The tracks are often as long as 300 km or more and about 9 km wide (Durkee et al. 2000). They typically form in relatively shallow boundary layers between 300–750 m deep. They do not form in boundary layers deeper than 800 m (Durkee et al. 2000).

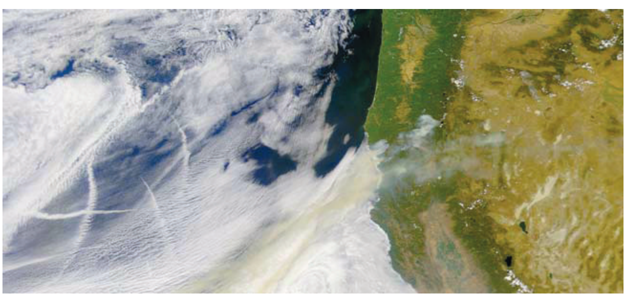

Figure 17.1 A number of ship tracks (i.e., clouds formed from the exhaust of ships' smokestacks) can be seen north and west of the smoke plume. Image courtesy of the SeaWiFS Project, NASA GSFC, and ORBIMAGE.

It Is Therefore Hypothesized That We Should Produce More Ship Tracks

The regions most susceptible to those changes are oceanic subtropical high pressure regions. One could redesign ship routes (with economic incentives) for high sulfur-containing coal-burning ships to sail along the windward regions of subtropical highs. These could be supplemented with additional "*albedo enhancer*" ships to sail back and forth along the windward side of marine stratocumulus cloud layers in the vulnerable regions. Research is needed to estimate the number of supplemental ships and economic incentive costs to achieve a desirable increase in global-averaged albedo. I expect the costs would be prohibitive. There is modeling evidence that not all clouds respond to increasing aerosol pollution with an increase in albedo (Jiang et al. 2002; Ackerman et al. 2004; Lu and Seinfeld 2005). Thus the science of cloud responses to aerosols must be advanced before this hypothesis could be implemented as a strategy. Of course, there are adverse consequences of purposely polluting clouds that we must consider, including acid drizzle, but at least the regions affected would be well offshore, away from most human activity.

The idea behind hygroscopic seeding of marine stratocumulus clouds is not new, as Latham (1990, 2002) proposed generating seawater drops around 1 μm in size near the ocean surface to enhance droplet concentrations. A spray of seawater drops would be produced either by high volume atomizers or blowing air through porous pipes to produce air bubbles that would rise to the sea surface and burst, much like a natural wave action produces the bubbles. The former technique has the advantage that one can be more certain that the salt particles thus produced would have an optimum size for competing with natural CCN and thereby increase droplet concentrations once the particles are lofted into clouds in the marine turbulent boundary layer. The advantage of this technique is that raw materials would be free and non-polluting. However, the production and movement of a large number of generating floats or derricks would be very costly indeed. Latham claims that the power requirements for their operation could be supplied by solar, wave action, or even wind power. He actually proposes the development of sailing ships based on the Magnus effect, where spinning towers would not only develop the aerodynamic lift to propel the ships but would also drive the sea-spray generators (Latham et al. 2008). Figure 17.2 presents an artist's concept of such Magnus force-based sailing ships designed for sea-spray generation. Rough estimates of the climatic effects of deploying a large ensemble of such ships to produce sea-spray over a large area have been made with a GCM. The GCM, however, does not consider possible negative dynamic responses, such as enhanced entrainment or those that will result from alterations in drizzle, which cloud-resolving simulations have suggested (Jiang et al. 2002; Ackerman et al. 2004; Lu and Seinfeld 2005). Thus, the GCM estimates probably err on the side of yielding a greater cooling effect than can be achieved in reality.

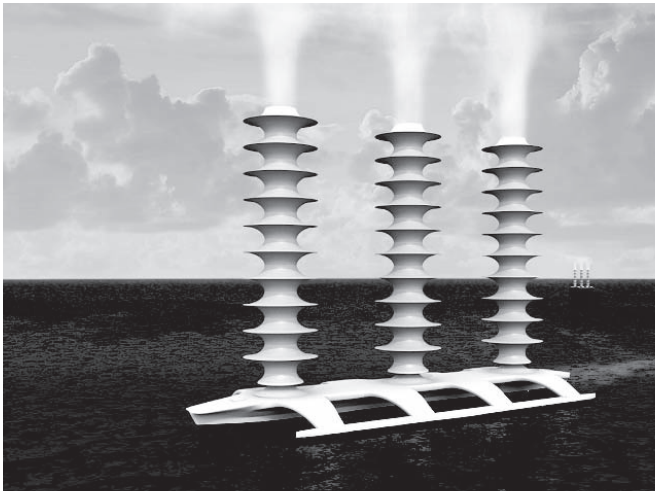

Figure 17.2 Artist's concept of a Magnus-effect sailing ship for sea-spray generation. From Latham et al. 2008; used with permission from the artist, John MacNeill.

Overall, the approach to climate engineering using hygroscopic seeding concepts is worth examining more fully with models and limited field experiments. I must admit to being skeptical that one could implement such a strategy on a near continuous basis over large enough areas to counter greenhouse warming significantly.

Mid-level Stratus Seeding

Mid-level stratus clouds, also called altostratus, are ubiquitous throughout large regions of the middle latitudes. A typical elevation of these clouds is about 3 km above sea level, and during the cold seasons many of these clouds are supercooled. Normally, mid-level stratus are thought to play a neutral role in the Earth's radiation budget since they reflect about as much solar radiation as they absorb longwave radiation. However, this near radiative balance might be upset by worldwide selective cloud seeding. For instance, consider non-freezing stratus clouds: One can imagine a systematic seeding of these clouds by day with pollution aerosols (small hygroscopic particles) to increase their albedo and by night seed with giant CCN or conventional hygroscopic seeding materials to cause them to rain-out, thereby making them more transparent to longwave radiation. This would shift their contribution to the global radiative balance to a net cooling effect. A similar strategy could be followed for supercooled stratus. In that case, one could again seed with pollution aerosols during the daytime to increase their albedo but at night seed with glaciogenic seeding materials, such as AgI. It has been shown a number of times that seeding supercooled stratus will reduce the total condensate path of those clouds, thus making

Figure 17.3 This racetrack pattern, approximately 20 miles long, was produced by dropping crushed dry ice from an airplane. The safety pin-like loop at the near end of the pattern resulted when the dry ice dispenser was inadvertently left running as the airplane began climbing to attain altitude from which to photograph results. From Havens et al. (1978). Photo, taken in 1948, used with permission from Dr. Vincent Schaefer.

them more transparent to longwave radiation. Figure 17.3 shows a classic example of clearing supercooled stratus by seeding with glaciogenic materials.

How could this be done globally in a cost-effective manner? Some industries with tall stacks could have their affluent doped with the appropriate aerosol. Use of commuter aircraft with their jet fuels doped with aerosol generators is another possibility. Also, the use of unmanned aerial vehicles or blimps for aerosol dispersal could be considered. Potential adverse consequences, however, are likely, including impacts on precipitation, local cold temperature extremes (which would also impact fossil fuel demands), and the hydrological cycle.

Overall, this approach to countering greenhouse gas warming is more costly and less feasible than hygroscopic seeding of marine stratocumuli.

Seeding Cirrus Clouds or Making More Contrails

On an annual average, clouds cover between 60–65% of the Earth (Rossow and Dueñas 2004) and much of that cloud cover consists of middle and high clouds. It is thought that cirrus clouds contribute globally to a warming of the atmosphere due to their contribution to downward transfer of longwave radiation. In other words, they act as a greenhouse agent. Human activity is already modifying cirrus clouds through the production of aircraft contrails. Kuhn (1970) found that contrails depleted solar radiation and increased downward longwave radiation, but during the daytime their shortwave influence dominates and they contribute to a net surface cooling. Kuhn (1970) calculated that if contrails persist over 24 h, their net effect would be cooling. Others have concluded that they lead to surface warming (Liou et al. 1991; Schumann 1994), but Sassen (1997) notes that the sign of the climatic impact of contrails is dependent upon particle size. Global estimates of the effects of contrails are that they contribute to a net warming (Minnis et al. 2004).

It has even been proposed seeding in clear air in the upper troposphere to produce artificial cirrus, which would warm the surface enough to reduce cold-season heating demands (Detwiler and Cho 1982). Thus the prospects for seeding cirrus to contribute to global surface cooling do not seem to be very good.

The only approach that might be feasible is to perform wide-area seeding with soot particles, which would absorb solar radiation and warm cirrus layers enough to dissipate perhaps cirrus clouds. This strategy would be similar to that proposed by Watts (1997) and Crutzen (2006) for implementation in the stratosphere. As noted by Crutzen (2006), only 1.7% of the mass of sulfur is needed to produce a similar magnitude of surface cooling. Application at cirrus levels in the upper troposphere would have the double benefit of absorbing solar radiation, thus contributing to surface cooling and dissipating cirrus clouds which would increase outgoing longwave radiation. Of course, the soot that becomes attached to ice crystals would reduce the albedo of cirrus, thus countering the longwave warming effect to some degree. In addition, there is evidence that soot particles can act as ice nuclei, thus contributing to greater concentrations of ice crystals by heterogeneous nucleation but possibly reduced crystal production by homogeneous nucleation (DeMott et al. 1994; Kärcher et al. 2007). Thus it would be best to engineer carbonaceous aerosol to be ineffective as ice nuclei.

The possible adverse consequences of such a procedure can only be conjectured at this time but are most likely to impact the hydrological cycle. Complex chemical, cloud-resolving, and global models are required to evaluate the feasibility of this approach and to estimate possible adverse consequences. The feasibility of this approach in terms of implementation strategies is probably comparable to seeding sulfates in the lower stratosphere. The costs would be similar to Crutzen's estimates for stratospheric seeding.

Summary and Recommendations

In this chapter, I have provided an overview of both weather engineering (cloud seeding) and climate engineering. I have shown that there are a number of lessons learned from cloud seeding evaluation, such as that *both* strong physical evidence of appropriate modifications to the climate system and highly significant statistical evidence are required. This will be quite challenging, as I find it hard to imagine that randomized statistical experiments can be designed and implemented for long enough time periods to isolate the modification signals from the background "natural variability" of the climate system.

As I mentioned above, if we as a scientific community require the same standards of "proof" imposed on the weather modification community for evaluating cloud seeding hypotheses as for evaluating whether human-produced greenhouse gases are changing climate (which I think we should), we are a long way from being able to say that CO_2 is altering climate. Likewise, for firm "proof" that climate engineering is affecting climate, the required levels of physical model evaluations and statistical evaluations will be extremely challenging. What is needed, first of all, is a demonstrated climate model forecast skill that is large enough to be able to extricate the climate modification signal from the "natural variability" or "noise" of the climate system. Once this predictive skill is achieved, then there is the opportunity to apply advanced statistical methods that use model–output statistics and observed response variables that can confirm the hypothesis. Moreover, this climate forecast model should be able to identify and quantify unexpected undesirable consequences of climate engineering.

Alan Robock (2008) recently wrote a paper entitled "Twenty Reasons Why Geogenineering May be a Bad Idea." He notes that one possible response to climate engineering to mitigate greenhouse gas warming is that precipitation is likely to be modified both globally and regionally. Some countries may find themselves in a drought in response to climate engineering. Many of the cloud-related climate engineering hypotheses are likely to impact the hydrological cycle, especially those hypotheses associated with modification of mid- and high-level clouds. Other reasons listed by Robock (2008) were:

- Continued ocean acidification.
- Ozone depletion.
- Effects on the biosphere.
- Enhanced acid precipitation.
- Effects on cirrus clouds (reference to S seeding in the stratosphere).
- Whitening of the sky (reference to S seeding in the stratosphere).
- Less solar radiation for solar power, especially for those requiring direct solar radiation.
- Rapid warming when it stops.
- How rapidly could effects be stopped?
- Environmental impacts of aerosol injection.
- Human error.
- Unexpected consequences.
- Schemes perceived to work will lessen the incentive to mitigate greenhouse gas emissions.
- Use of the technology for military purposes.
- Commercial control of technology.
- Violates current treaty.

- Would be tremendously expensive.
- Even if it works, whose hand will be on the thermostat? How could the world agree on the optimum climate?
- Who has the moral right to advertently modify the global climate?

In regard to unexpected consequences, I have already stated that I do not believe that we understand all the factors that effect climate variability nor have we demonstrated a climate forecast skill to merit implementing a climate warming mitigation strategy. What if I am right that volcanic activity is a major "wild card" in the climate system? Now, suppose we implement one of the climate engineering concepts outlined above to cool the planet in opposition to greenhouse warming. If successful, this cooling will lead to ocean responses on timescales of decades to perhaps a century. In the meantime, suppose we find ourselves in the midst of a period of enhanced volcanic activity. The cooling trend following volcanic activity combined with our "engineered" cooling trend could drive us into a Little Ice Age or worse. I expect the consequences of that would be far worse than global warming.

Despite these concerns, climate engineering is an issue that cannot be ignored. The gravity of this situation is emphasized by the fact that any of the aerosol- or cloud-related climate engineering schemes would have to be continued for centuries because of the long atmospheric residence times of the atmospheric greenhouse gases. I recommend that major international initiatives be planned throughout the world, using the most advanced models in the design of specific climate engineering projects. Before climate engineering can, however, be implemented, fundamental research must first advance our *quantitative* understanding of the climate system, of climate variability, the scientific possibilities of climate engineering, technical requirements, social impacts, and requisite political structures needed. Climate engineering should be considered a "last gasp" measure to prevent catastrophic consequences of a changing climate.

Another lesson learned from cloud seeding, which I have not mentioned previously, is that cloud seeding is often called upon by politicians to demonstrate *that they are doing something* during periods of drought and major water shortages or following major catastrophes. This has occurred despite the lack of strong scientific evidence that cloud seeding actually works. I refer to this as the use of *political placebos*. If we find ourselves in a true climate crisis, I anticipate that politicians will call for climate engineering measures to alter the adverse climate trends. If this should ever be the case, let us be sure that we act based on the most advanced level of knowledge of the climate system as well as of the full consequences of our actions.

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