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GEOENGINEERING THE CLIMATE

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Abstract

Although much can be done to limit greenhouse gas emissions by conservation, improvements in efficiency, and use of alternative technologies, the use of fossil fuels at rates even sharply reduced from U.S. per capita values will lead to rapidly increasing global concentrations of greenhouse gases. The available alternatives then become adapting to the changes, switching to alternative energy sources (e.g., solar, nuclear), or actively taking control of atmospheric composition and/or the climate. This note reviews options for geoengineering the climate.

Introduction

The increasing concentrations of greenhouse gases and the consequent climatic changes and ecological and environmental impacts may pose a very significant challenge to a wide-range of vital societal activities. Normally, the preferred course of action is to curtail or halt activities that may lead to adverse impacts. Because significant curtailing or halting of at least some of these activities may pose unacceptable costs to the nations of the world, particularly those of large developing nations, other options merit full exploration.

Geoengineering—that is actively intervening to counteract the chemical and/or climatic changes caused by greenhouse gas emissions—is one such option. For several reasons, this is a particularly controversial option. Some see it as an illusory escape, for "greenhouse junkies," distracting attention from more conventional and possibly more cost-effective strategies that have a better chance of gaining international acceptance, given the multitude of cultural and economic viewpoints and the variable pattern of beneficial and negative impacts. Even if investigated, the uncertainties in projecting the greenhouse change are generally amplified when projecting potential responses to any proposed intervention, with no assurance that all indirect effects and potential surprises can be predicted. Others are concerned about mortgaging future generations with such strategies, and the increasing impacts of failing to maintain such interventions. Still others are concerned about the potential irreversibility of any intervention. And still others simply do not trust that technology can extract society from a problem that technology created.

Technological optimists counter that understanding the potential options is an important insurance policy in case the effects and impacts prove very large or if the costs of more conventional measures are excessive or not sufficiently effective. Even if innovative conventional measures reduce per capita carbon requirements for sustaining an acceptable lifestyle to 25% of present U.S. levels, the increasing population levels expected would lead to more than a doubling of present carbon emissions (and probably a tripling due to the use of coal) over the next 50 years. Estimating the magnitude of counterbalancing geoengineering schemes would also increase understanding of the magnitude of the inadvertent geoengineering that is now underway and may provide a perspective that might increase impetus for implementing the full range of more conventional options. If designed properly, geoengineering options should be reversible and be able to be implemented incrementally, so should be able to avoid problems of irreversibility (or near irreversibility) of the inadvertent modifications caused by emission of greenhouse gases.

Investigation of geoengineering options would, thus, provide information for informed choices, helping resolve questions that will continually arise and which may cause delays and inaction if not addressed forthrightly. In any case, in that we are already inadvertently geoengineering the climate, we should fully understand the range and potential for advertent modification in case we somehow determine that the present or a future, naturally cooling, climate are not optimal.

Range of Options

The set of options for geoengineering the climate can be subdivided into several categories. These include:

A. Engineering atmospheric composition;
B. Engineering external climate forcing factors
C. Engineering climate feedbacks and processes (internal factors); and
D. Engineering climate system responses.

The first of these categories would consider approaches such as directly capturing and sequestration of emissions, actively removing greenhouse gases from the atmosphere by either enhanced biological sequestration (e.g., in soils, forests) or by direct destruction (e.g., laser destruction of CFCs), and other measures. These geochemical engineering options will be covered by other contributions to this volume. This note will instead focus on geophysical options, which have also recently been reviewed in NAS (1991).

Engineering External Climate Forcing Factors

In evaluating the potential applicability of the options suggested below, it is helpful to understand the magnitudes of important fluxes. Radiation models estimate that doubling of the atmospheric carbon dioxide concentration will increase the net trapping of infrared radiation at the tropopause* by about 4.4 W/m^2. To date, the IPCC (1990) estimates that the increases in concentrations of greenhouse gases since 1765 have increased the trapping of IR radiation by about 2.45 W/m^2. For geoengineering schemes to be effective, they must be capable of counterbalancing fluxes of comparable amounts. For reference here,

* The tropopause is the boundary between the troposphere and the stratosphere, which is generally located about 10–15 km altitude, depending on latitude and season. The change of flux at the tropopause is important because the troposphere and surface are convectively coupled such that the change in flux at the tropopause affects the coupled system.

schemes will be evaluated based on their ability to counterbalance 2.2 W/m^2, or the equivalent of half of the flux change due to a doubling of the CO_2 concentration.

The primary external climate forcing factor is solar radiation. One advantage of dealing with solar radiation is that experience with the seasonal and diurnal cycles and with volcanic eruptions provides some insight into what would need to be done and what possibilities exist. Means of reducing the absorption of solar radiation by the surface-atmosphere system have been suggested that would have their effect in space, in the atmosphere, and at the surface. Table 1 provides estimates of various terms in the solar radiation budget for use in estimating the magnitude of change required by geoengineering schemes.

Table 1. Estimated solar flux components (W/m^2).

Solar insolation (top of the atmosphere)			342
Solar radiation reflected to space (29% albedo)		100	
Clear sky fraction (50%)			
Surface (13% albedo)	32		
Clouds	0		
Atmosphere (backscattered 7%)	24		
Total	56	× .5 = 28	
Overcast sky fraction (50%)			
Surface	0		
Clouds	133		
Atmosphere (above clouds) (4%)	12		
Total	145	× .5 = 72	
Solar radiation absorbed by atmosphere (23%)		78	
Solar radiation absorbed by surface (48%)		164	
Total allocation of solar insolation			342

Notes:

1. Overcast minus clear sky effects, when averaged over the planet, give a global average cloud effect of -44 W/m^2, in agreement with ERBE results.
2. A 1% change in the solar constant is equivalent to $.01 \times 340 \times (1-.29) = 2.4$ W/m^2 (or about half of the radiative flux change of a CO_2 doubling).

A. Space

From an energetics consideration, reducing the incoming solar flux in space is most attractive because the flux is greatest and, therefore, the size of the intervening mechanism can be least. However, implementing such a scheme requires lofting and sustaining the required materials into orbit. Schemes suggested include:

1. *Orbiting mirrors.* The NAS (1991) proposed that 50,000 mirrors, each with a surface area of 100 km^2, be lofted into near Earth orbit. Assuming randomly oriented orbits with the mirrors oriented parallel to the surface, this would give total coverage of 5×10^6 km^2, which is about 1% of the Earth's surface. As a result, the mirrors would intercept 1% of the incoming solar radiation. If aligned perpendicular to the incoming solar flux, or placed preferentially in low latitude orbits, about 2% of the incoming solar radiation could be intercepted. The large number of mirrors would permit incremental implementation. Such mirrors would, however, create shadows on the surface roughly equivalent to eclipses; such events would be quite frequent and probably troubling, even accounting for diffraction effects. A greater number of smaller mirrors could be used to alleviate this problem, but the effort to launch and to keep separated so many mirrors becomes larger. Removing the mirrors from orbit would require a significant effort, making this a difficult intervention to reverse.

2. *Orbiting layer of absorbing or scattering particles.* One could place in orbit a cloud of soot particles that would absorb solar radiation. Assuming a specific absorption of 10 m^2/g and requiring coverage of 5×10^6 km^2 in order to absorb 1% of the incoming solar radiation would require 5×10^8 kg to be placed in a dispersed orbit; for scattering particles, the amount would be somewhat larger. Injections could be done incrementally as greenhouse concentrations rise. Keeping the particles in orbit might well be difficult, however, due to the solar wind and other effects. In addition, such particles would significantly pollute near-Earth orbits. There would also be virtually no means for reversing the process; the particles would move on their own until being removed through contact with the atmosphere. Inspired by Hoyle (1957), Kahle and Deirmeudjian (1973) considered the consequence on atmosphere conditions of a relatively thick absorbing layer that affected only solar radiation. The effects of the IR emissions from soot particles particularly may compensate some of the solar effect and deserve consideration.

3. *Solar deflector at the Lagrange point.* Early (1989) proposed that a 2000 km diameter solar shield made of lunar materials be placed at the first Sun-Earth Lagrange point (1.5×10^6 km from Earth). The shield would deflect 2% of the radiation incident on the Earth (deflection instead of reflection to reduce the impact of the solar wind) and would be essentially unnoticeable from the Earth due to its relatively small size. Early (1989) estimates that a 10 μm thick shield would weigh 10^{11}kg and cost from 1 to 10 trillion dollars. Moving the shield would be relatively inexpensive, so the phenomena is reversible; the incremental effect could be achieved by tilting of the deflector to reduce cross-sectional area. A major problem with this proposal is the upfront cost before any effect is created.

All of these schemes would also reduce the uv flux, which would lead to less stratospheric ozone, which would in turn slightly amplify the warming being countered. Other chemical effects would also require consideration.

B. Atmosphere

The prime difficulty with modifying the solar radiation fluxes in the atmosphere is keeping the modifying material aloft. Because large structures would require large amounts of energy to keep them aloft, resort must be made to either very small particles (~ 0.1 μm) that have very slow removal times or be kept aloft with balloons that are evacuated or filled with hydrogen, helium, or other low molecular weight gases.

1. *Reflective stratospheric aerosols.* The suggestion to inject sulfate aerosols goes back to at least SMIC (1971), Budyko (1974), and Dyson and Marland (1979). Such a human volcano could lead to significant backscattering of solar radiation. Broecker (1985) estimated the amount of sulfur required that needed to be carried aloft by special aircraft, and how this sulfur could be added as a component of existing jet fuel and emitted by commercial aircraft, NAS (1991) evaluates various lofting schemes, including balloon systems and launch by artillery pieces. Alternately, the sulfur could be emitted at the surface as COS and allowed to mix upward and be transformed to $SO_4^=$. For injection altitudes in the lower stratosphere, the particle lifetimes would likely be less than a year (based on lifetimes of volcanic aerosols), so the effect would be naturally reversible and could be implemented incrementally. (Injection into the troposphere is presently occurring as a result of fossil fuel combustion by the commercial aircraft fleet, but would generally not be preferred for geoengineering consideration due to the rapid removal time of sulfates from this altitude.) However, because much of the scattering is forward, the sky would become more white, with direct solar radiation reduced substantially even when total radiation is reduced only modestly. The large dimunition of direct solar radiation would negatively affect solar energy sources relying on direct radiation and astronomers would also likely object to the increased scattering, although the public might appreciate the enhanced color of sunsets due to the scattered radiation. The amount of sulfur injected would be well less than that now causing "acid rain" and would be dispersed rather than concentrated, and thus would not create problems when rained out. However, the aerosols in the stratosphere would likely be a sink for stratospheric ozone.

2. *Absorptive stratospheric aerosols.* Much in the manner of "nuclear winter" aerosols (Turco et al., 1983), injection of soot into the stratosphere would lead to cooling of the lower atmosphere, although account would need to be taken of the increased downward IR flux. Again, the implementation could be incremental, but the modification of the temperature structure might lengthen removal times. The heating of the stratosphere would also perturb stratospheric chemistry in ways deserving attention.

3. *High altitude balloons.* NAS (1991) suggests stratospheric injection of small (few meter diameter), thin-skinned, helium-filled aluminum balls to reflect solar

radiation. Larger balloons could be used, but might impose flight hazards. The implementation could be incremental, but the removal rate would be determined by the lifetime of the balloon (and its lifting capability) rather than by natural removal processes. The non-selective directional scattering of the balloons could be made more efficient by using corner reflectors to enhance the effect of the lower sphere of the balloon (see Canavan and Teller, 1991); in this case incoming solar would be reflected back to space without scattering, which would eliminate several problems associated with aerosols and spherical balloons. Both shapes, unless specially designed, would backscatter (or absorb and reradiate) radiation outside the visible, including natural IR and manmade radio and other wavelengths; this could be an advantage or disadvantage, depending on how used (using corner reflectors with angles slightly different than 90° would be needed to prevent interference with transmitters on the surface; spherical shapes might be of great assistance for ham radio, etc.). The balloons could alternatively be filled with hydrogen (except that escape would lead to stratospheric water vapor) or might be evacuated, which would require construction and insertion at altitude and ultralight construction materials (e.g., aerogels) to avoid weight penalties for an evacuated chamber. A question that must be resolved is to determine the optimum altitude (or altitudes) or mechanism that will limit advective accumulation of the balloons in polar areas (at the proper level, the circulation changes as seasons evolve may ensure adequate distribution).

4. *Reflective tropospheric aerosols.* Preliminary calculations indicate that current emissions of SO_2, largely from fossil fuel combustion, are exerting a cooling influence on the climate (Charlson et al., 1990). Enhancing such emissions would therefore appear to offer the potential for greater cooling. The injected aerosols would need to be pure SO_2 and/or sulfate because contamination by even small amounts of absorbing aerosols (e.g., soot) would generally tend to change the cooling effect to a warming effect. The additional SO_2 could be injected by additional releases from existing power plants (although if regionally concentrated, "acid rain" and visibility degradation become concerns) or could be specially injected into the Southern Hemisphere troposphere so that their effects and impacts on visibility and acid deposition would occur primarily over unpopulated ocean areas. To be effective, such emissions should be lofted as much as possible; smoldering combustion at the surface to create aerosols would be generally ineffective as well as undesirable due to the injection of other pollutants. Because tropospheric aerosols are generally removed from the atmosphere in days to weeks, the injections would have to be continuous (although one might inject only in low latitudes and only during the summer in mid-latitudes when solar radiation is most intense) and in rather large amounts. (To achieve a Southern Hemisphere burden of 0.01 g/m^2, assuming a five day lifetime, would require an injection rate of about 180 million tons of sulfur per year!) It is also not certain how the atmosphere would respond to such changes in forcing; cloud and humidity changes might well result.

Overall, the schemes involving injection of aerosols, while relatively straightforward and generally only amplifying inadvertent and/or natural forcings thatare already occurring, have a number of difficulties. The potential effectiveness of corner-reflecting stratospheric balloons has yet to be thoroughly evaluated.

C. *Surface*

Energetically, the surface is the least efficient location to modify the global radiation balance because only about half of the solar radiation reaches the surface; the relatively low energy requirement to deploy the system would provide a counter balancing advantage were it not for the extensive use of the surface for other purposes.

1. *Whitening the land surface.* The four largest land use types, in order of increasing natural albedo, are forests, grasslands, deserts, and snow and ice-covered areas. Since the start of agriculture, human actions have been changing surface land use and its albedo. These inadvertent changes have surely affected climates, but only on a local scale are they likely significant. In considering potential advertent actions, preserving high albedo snow-covered areas is clearly desirable (but will be difficult with warming temperatures), but transforming forests or grassland to deserts would have many detrimental side effects. An alternative approach may be to increase the albedo of vegetation (via genetic engineering or substitution), an approach that may be feasible without reducing overall productivity in regions (e.g., equatorial regions) where available sunlight exceeds the amount now being used. Although modification of the *global* radiation balance over the land surface is problematic, modification of the local land surface to reduce urban heating (and thereby reduce air conditioning demand) does appear promising.

2. *Whitening the ocean surface.* The ocean covers about 70% of the Earth's surface and has a low reflectivity typically ranging from 5 to 10%. Increasing the albedo of the ocean surface via films, foams (Jones, 1990), or biological organisms would have many other important effects (e.g., altering the carbon and nutrient cycles and evaporation); making sea ice in high latitudes (by taking advantage of the cooling potential of the polar winter temperatures) and then hauling the sea ice to lower latitudes may be possible for limited areas.

Covering large areas of the ocean (roughly 10% per CO_2 doubling) with highly reflective floating chips or spheres is perhaps conceptually feasible (and reducing solar warming of the ocean would hopefully limit sea level rise), but such an approach would likely be aesthetically unacceptable in contrast to other options because the reflectors would have to be dispersed widely to achieve a uniform effect. Such floating materials would also likely accumulate on ocean shores rather than maintaining reasonable coverage.

An alternative, more natural approach might involve moving of icebergs from high to low latitudes, but it would involve moving roughly the entire Arctic icesheet each year to have a sufficient effect.

Engineering Climate Feedbacks and Processes

Although the underlying cause of the greenhouse-induced climatic change is the modification of the infrared radiation balance by the increasing concentrations of greenhouse gases, it is the response of atmospheric, oceanic, cryospheric, and land surface processes and feedbacks that determines the actual changes that take place. Thus, modifying the processes that are internal to the climate system offers a potential path to controlling or influencing the greenhouse response. The most important, and perhaps overwhelming, difficulty with this approach is the very close coupling of many processes in ways that are only poorly understood, so that even if modification were possible, predicting the consequences and side effects is very difficult and uncertain. Nonetheless, there appear to be several potential modifications to which the climate system might be sensitive.

1. *Atmospheric Processes*. Two possibilities to gain control of the climate by intervening in atmospheric processes involve either cloud modification (see NAS, 1991) or reduction of the atmospheric water vapor burden. An increase in the sulfate aerosol burden of the atmosphere may brighten clouds, particularly marine stratus decks, by increasing the number density of cloud droplets, although this may also lengthen the lifetime of water vapor in the atmosphere and enhance the water vapor greenhouse effect. Koenig (1974) conducted a model simulation to investigate inadvertent changes on a regional scale; more recently, Charlson et al (1991) evaluate global scale effects of current sulfur emissions.

It is often thought that increasing evaporation rates, for example in low latitude ocean or tropical land areas, may increase cloudiness (thereby increasing solar reflection), but cloud amount and location are typically controlled by relative humidity, vertical stability, and atmospheric circulation, rather than by absolute humidity; as a consequence, attempting to increase evaporation (for example by placing floating wicks in the ocean) may have little effect. It may actually be more effective to reduce the atmospheric water vapor burden and the water vapor greenhouse effect. This might be attempted by creating a monomolecular slick on the ocean to inhibit evaporation. This would, of course, lead to reduced rainfall, which is generally viewed as detrimental, and might not even reduce the atmospheric water vapor burden if the lifetime increases, which might occur unless the atmospheric cloud condensation nuclei burden is also reduced. In addition, any reduction in water vapor and/or cloudiness would also allow more solar radiation to reach the surface, where it would be susceptible to the maximum greenhouse effect.

2. *Oceanic Processes*. The ocean transports heat from low to high latitudes and buffers climatic change by taking up heat. A large global ocean conveyor belt (Broecker, 1991) carries heat and chemical constituents from the upper to deep oceans and back again. Heat transport and release in the North Atlantic, for example, helps warm Europe in the winter while cooling lower latitudes. Enhancing the strength of the conveyor belt would thus warm high northern latitudes during the cool seasons while moderating any warming in lower latitudes. Because the conveyor belt

is apparently driven by a salt excess (or fresh water deficit) in the North Atlantic basin, this situation could be enhanced by either damming the Bering Strait (where relatively fresh water enters) or by diverting rivers (e.g., in Siberia; see Lamb, 1971) which carry fresh water into the Atlantic so that their moisture is carried to the Pacific (e.g., by evaporating the water as a side effect of its use for irrigation). Reducing glacial calving and drainage from Greenland (e.g., via a preservative coating) would have a similar effect as well as moderating sea level rise. Enhancing the conveyor belt circulation might also help moderate sea level rise by reducing downward heat transport in the ocean gyres.

3. *Cryospheric Processes.* The sea ice, snow cover, glaciers, and polar ice sheets play several important roles. These include the reflection of solar radiation, the limiting of cooling of the polar ocean by the insulating effect of sea ice, the protection of land from freezing as deeply when under snow cover, the inhibition of evaporation of moisture (which limits cloud formation in polar regions), and the storing of water above sea level. Although somewhat surprising, the present seasonal cycle of sea ice seems to exert a warming effect on the climate system by insulating the polar ocean in the winter (thereby retaining its heat) and by a lowered albedo in the summer (thereby allowing increased solar absorption). If this cycle could be reversed, this warming effect of sea ice could be reversed. One way to do this would be to use pumps to carry water from below the sea ice and to spray it such that it comes out as snow or ice particles on the top of the sea ice. This process would bypass the insulating effect in the winter and provide thicker sea ice with its higher albedo to reflect summer radiation. Although such pumping may require energy, it may be possible to use ice-water temperature gradients to derive the energy. One potential question to be assessed is what would happen to the salt; the expectation is that it would melt through the ice, which might affect sea ice structure.

4. *Land Surface Processes.* Although the land surface exerts important effects on the atmosphere, altering existing interactions to affect global climate would require significant changes over very large areas. Aside from potential albedo changes, which were discussed earlier, changing the surface moisture balance might be considered (and has been carried out since the start of irrigation). On a global basis, reducing evaporation might help reduce the water vapor greenhouse effect; on a local basis, increasing evaporation (e.g., via irrigation) is known to reduce temperatures.

Overall, modifying climate system processes and feedbacks involves a complex set of interacting that are very difficult to evaluate and assess.

Engineering Climate System Responses

An alternative to preventing climatic changes is to geoengineer the responses to the change. The responses can generally be classified as temperature, precipitation and storms, and sea level.

1. *Temperature.* Global temperature modification by means other than those already mentioned does not seem feasible. However, local actions to adjust the

temperature via albedo or moisture changes can be effective. Alternatively, air conditioning has become the primary way to protect members of society from high temperatures.

2. *Precipitation and Storms*. Although model projections are uncertain, it appears that storm tracks will change in location and, perhaps, in intensity. In addition, it has been suggested that severe storms such as hurricanes may increase in frequency and/or intensity (Emanuel, 1987). Development of storm modification and rainfall enhancement activities, which are not now possible, may be able to provide the capability for amelioration of severe situations.

3. *Sea Level*. Projections suggest potential sea level rise of up to about 1 m by 2100. Areas below sea level that could be flooded with sea water are too limited to displace more than a very small amount of the projected rise. In fact, reductions in groundwater and reservoir volumes (due to siltation) are probably playing a small role in increasing sea level. Mountain glaciers may contribute a significant fraction to the projected sea level rise, so that preserving (or enhancing) such mountain glaciers would be helpful. Similarly, protecting the Greenland and Antarctic ice caps would be helpful.

An active approach to counteracting sea level rise from greenhouse gases could be undertaken by pumping ocean water and spraying it as snow onto the East Antarctic ice cap. This would require pumping of up to about 3 trillion tons of ocean water per year up several kilometers and onto the icecap, which would add about 0.3 m depth (as water) per year to the East Antarctic ice cap. Such active movement of water would require substantial amounts of energy (almost certainly costing more than the damages from the rising sea level). However, it may be possible to enhance natural transport of ocean water up onto East Antarctic by adjusting (increasing, decreasing, or changing the shape) sea ice extent around the continent, which might more favorably reposition the storm tracks for snow build-up.

Overall, there is some potential for moving actively to moderate the impacts of the climate system, but these appear more feasible on local rather than global scales because energy requirements for intervening are large and side effects may be important.

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References

Broecker, W.S., 1985: *How to Build a Habitable Planet,* Eldigio Press, Palisades, NY.

Broecker, W.S., 1991: The great global conveyor. *Oceanography* (submitted).

Budyko, M.I., 1974: The method of climate modification. *Meteorology and Hydrology*, **2**, 91–97 (in Russian).

Canavan, G., and E. Teller, 1991: Distributed remote sensing for defense and the environment. *Nature* (submitted). Los Alamos National Laboratory Report LA-UR-91-1169 (Rev.), Los Alamos, NM.

Charlson, R.J., J. Langner, and H. Rodhe, 1990: Sulphate aerosol and climate. *Nature*, **348**, 22.

Charlson, R.J., J. Langner, H. Rodhe, C.B. Leavy, and S.G. Warren, 1991: Perturbation of the northern hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols, *Tellus* (in press).

Dyson, F.J., and G. Marland, 1979: Technical fixes for the climatic effects of CO_2. *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*, 111–118. U.S. Department of Energy Report CONF-770385, Washington, DC.

Early, J.T., 1989: Space based solar shield to offset greenhouse effect. Lawrence Livermore National Laboratory Report UCRL-100307, 8 pp (available from NTIS, Springfield, VA).

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483–485.

Hoyle, F., 1957: *The black cloud,* Harper and Brothers, New York, 250 pp.

Intergovernmental Panel on Climate Change (IPCC), 1990. *Climate Change: The IPCC Assessment*, 365 pp., J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (Eds.) Cambridge University Press, Cambridge, UK.

Jones, D., 1990: Firefighting foam. *Nature*, **348**, 396.

Kahle, A.B., and D. Deirmendjian, 1973: The black cloud experiment, Rand Corporation Report R-1263-ARPA, Santa Monica, 26 pp.

Koenig, L.R., 1974: A numerical experiment on the effects of regional atmospheric pollution on global climate, Rand Corporation Report R-1429-ARPA,.Santa Monica, 77pp.

Lamb, H.H., 1971: Climate-engineering schemes to meet a climatic emergency. *Earth Science Reviews*, **7**, 98–95.

National Academy of Sciences (NAS), 1991. *Policy Implications of Greenhouse Warming*, National Academy Press, Washington, DC (Synthesis Panel Report, 127 pp; and Report of the Mitigation Panel).

Study of Man's Impact on Climate (SMIC), 1971. *Man's Impact on Climate*, W.H. Matthews, W.W. Kellogg, and G.D. Robinson (Eds.), MIT Press, Cambridge, MA. 594 pp.

Turco, R.P., O.B. Toon, T. Ackerman, J.B. Pollack, and C. Sagan, 1983: Nuclear winter: global consequences of multiple nuclear explosions. *Science,* **222,** 1283–1293.

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