1.1 WEATHER AND CLIMATE ENGINEERING

William R. Cotton

Department of Atmospheric Science, Colorado State University, Fort Collins, CO

1. INTRODUCTION

I prepared a position paper on “Weather and Climate Engineering” for a workshop on “Perturbed Clouds in the Climate System” organized by the Frankfurt Institute for Advanced Studies (FIAS) held in Frankfurt, Germany in March 2008. The position paper will eventually be a chapter in a book. I think it is appropriate to share with the weather modification community the main points of this position paper. The position paper highlights the areas of greatest progress in weather modification research noting the major successes and failures. In this paper I will only mention the topics I covered and will focus on the lessons learned from cloud seeding that are relevant to climate engineering. I will mainly focus here on climate engineering which I define as a subset of the overall scheme of geoengineering dealing specifically with modifying the climate of Earth. I will conclude with recommendations and concerns I have about implementing climate engineering strategies.

I should note 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. Yet after over 50 years of research we cannot point to strong physical and statistical evidence that these early claims have been 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 still 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.

2. IMPLICATIONS OF CLOUD SEEDING RESEARCH TO CLIMATE ENGINEERING

After a review of deliberate cloud seeding concepts and experiments including *glaciogenic seeding* and hygroscopic *seeding* I summarized the implications of weather engineering to climate engineering as follows.

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

Another lesson from evaluating cloud seeding experiments is that “natural variability” of clouds and precipitation can be quite large and thus can inhibit conclusive evaluation of even the best designed statistical experiments. The same can be said for evaluating the effects of climate engineering or that human-produced CO_2 is altering climate. If the signal is not strong, then to evaluate if human activity has produced some observed effect (cause and effect), one requires much longer time records than is available for most if not all data sets. 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 we do not have an adequate measure of the “natural variability” of climate. Venturing into climate engineering recognizing that potentially large “natural variability” may exist is hazardous indeed.

Another less learned from cloud seeding that 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 is in spite of the lack of strong scientific evidence that cloud seeding works. I refer to this as the use of *political placebos*. I anticipate that if we find ourselves in a true climate crisis, that politicians will call for climate engineering measures that will alter the adverse climate trends.

3. CLIMATE ENGINEERING

I will only focus on climate engineering as it pertains to engineering changes in global albedo and top of the atmosphere longwave radiation emission by aerosols and cloud modification. I will not go into the broader context of geoengineering that 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 CO2 uptake in the oceans, carbon

---

Corresponding author address: William R. Cotton, Colorado State Univ., Atmos. Sci. Dept., Fort Collins, CO 80523; e-mail: cotton@atmos.colostate.edu

sequestration, alternate energies, or even changing the albedo of oceans and land-surfaces.

3.1 Emulating Volcanoes

Volcanoes are a major wildcard in the climate system. A major volcanic eruption distributes large quantities of dust and debris into the upper troposphere and lower stratosphere. More importantly they introduce large quantities of SO_2 into the lower stratosphere which undergo 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 reaching the surface. A single major eruption can produce a reduction in solar radiation that can last for something like two years and can result in residual heat loss in the ocean mixed layer for as long as 10 years.

The idea of introducing sulfate aerosols into the stratosphere goes back a number of years to Budyko (1974), Dyson and Marland (1979), and given more recent prominence by Nobel Laureate, Paul Crutzen (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. Crutzen estimates that 1.9 Tg S would be required to offset 1.4 W/m^2 warming by CO_2, which would reduce optical depth by 1.3%. He estimates that this can be achieved by continuous deployment of about 1-2 Tg S per year for a total cost of $25-50 billion. To compensate for a doubling of CO_2 (estimated $4W/m^2$ warming) Crutzen estimates 5.4 Tg S per year are needed with corresponding cost increases. Because scattering by these particles is by Rayleigh scattering we expect as with volcanoes that the sky will 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 reduced ozone by 16% at 20 km altitude whereas Mount Pinatubo which introduced 10 Tg S contributed to 2.5% reduction in column ozone loss. I imagine someone could translate that into rates of increased incidence of skin cancer by increased UV radiation amounts.

Another option noted by Crutzen (2006) and NRC (2003) would be to release soot particles in the lower stratosphere by burning, you guessed it, fossil fuels. Like the nuclear winter hypothesis (see review by Cotton and Pielke 2007), the soot particles would absorb solar radiation. This would deplete solar radiation reaching the surface but 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.

It has also been proposed to manufacture mirrors that are introduced in space (NAS 1992), and to introduce a solar shield at the Sun-Earth Lagrange point (1.5 x 10^6 km from Earth)(Early,1989) but I will not focus on these hypotheses and instead keep the discussion focused more on cloud seeding related strategies.

3.2 More ship tracks!

The strongest evidence that we have that pollution aerosols increase cloud albedo is from ship tracks. Figure 1 shows a typical ship track. In fact, Porch et al. (1990) referred to them as the *rosetta stone* connecting changes in aerosol over the oceans and cloud albedo effects on climate.

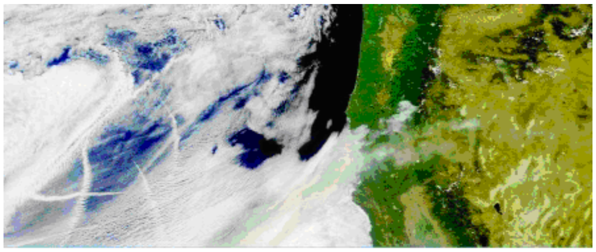

Figure 1. A number of ship tracks—clouds formed from the exhaust of ships' smokestacks—can be seen north and west of the smoke plume. [Image courtesy of the SeaWiFS Project, NASA GSFC, and ORBIMAGE.]

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 300m and 750 m deep. They do not form in boundary layers deeper than 800 m (Durkee et al. 2000). *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. Then of course there are the adverse consequences of purposely polluting clouds including acid drizzle. At least the regions affected would be well offshore away from most human activity.

The idea of hygroscopic seeding of marine stratocumulus clouds is not new as Latham (1990; 2002) proposed generating sea water drops around 1μm in size near the ocean surface to enhance droplet concentrations. A spray of sea water drops would be produced either by high volume atomizers or blowing air through porous pipes that would produce air bubbles that would rise to the sea surface and burst much like natural wave action produces the bubbles. The former technique has the advantage that one can be more certain that the salt particles so 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. But the production and movement of a large number of floating generating floats or derricks would be very costly indeed. Latham claims the power requirements for their operation could be supplied by solar or wave action, or even wind power. They actually propose development of sailing ships based on the Magnus effect wherein spinning towers would not only develop the aerodynamic lift to propel the ships but drive the sea-spray generators (Latham et al. 2008). Figure 2 is 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 dynamical responses such as enhanced entrainment and as a result of alterations in drizzle that cloud-resolving simulations have suggested (Jiang et al. 2002; Ackerman et al. 2004; Lu and Seinfeld 2005). Therefore, the GCM estimates probably error on the side of yielding a greater cooling influence than can be achieved in reality.

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 nearly continuously over large enough areas to significantly counter greenhouse warming.

3.3 Mid-level stratus seeding

Mid-level stratus clouds, also called altostratus, are ubiquitous throughout large regions of middle latitudes. A typical elevation of these clouds is about 3 km MSL and during the cold seasons many of these clouds are supercooled. Normally middle level stratus are thought to play a neutral role in the earth's radiation budget as they reflect about as much solar radiation as they absorb longwave (LW) radiation. However, this near radiative balance might be upset by worldwide selective cloud seeding. For instance, consider non-freezing stratus clouds. One can imagine 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 LW 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 them more transparent to LW radiation. Figure 3 shows a classic example of clearing supercooled stratus by seeding with glaciogenic materials.

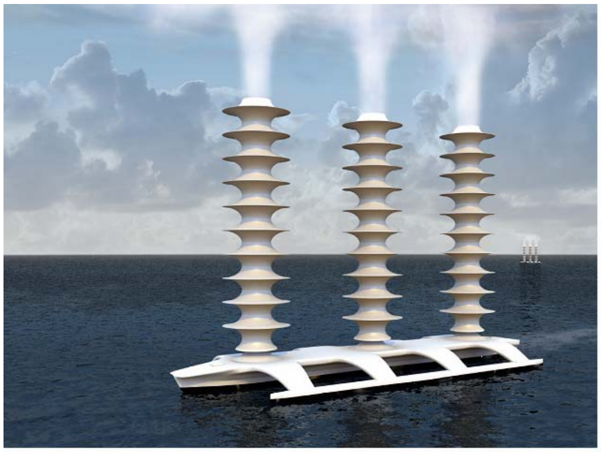

Figure 2. Artist's concept of a magnus-effect sailing ship for sea-spray generation. [From Latham et al. 2008. Used with permission from artist John MacNeill.]

A question is how could one do this globally in a cost-effect 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 UAVs 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.

Figure 3. Racetrack pattern approximately 20 miles long 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 courtesy of Dr. Vincent Schaefer.]

3.4 Seeding cirrus clouds or making more contrails

On an annual average clouds cover between 55 to 60% of the earth (Matveev 1984) and much of that cloud cover consists of middle and high clouds. It is thought that globally cirrus clouds contribute to warming of the atmosphere owing to their contribution to downward transfer of LW radiation. In other words they are a greenhouse agent. Human activity is already modifying the cirrus clouds through the production of aircraft contrails. Kuhn (1970) found that contrails depleted solar radiation and increased downward LW 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 24h 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 they contribute to a net warming (Minnis et al. 2004).

It has even been proposed to seed 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). So 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 or carbonaceous aerosols which would absorb solar radiation and warm cirrus layers enough to perhaps dissipate cirrus clouds (a semi-direct effect). 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 will 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 IN.

The possible adverse consequences of such a procedure can only be conjectured at this time but are mostly 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.

4. CONCLUSIONS

In this paper I summarized the lessons learned from weather engineering (cloud seeding) and reviewed climate engineering. I have shown that there are a number of lessons learned from cloud seeding evaluation such as *both* strong physical evidence of appropriate modifications to the climate system and highly significant statistical evidence is 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 have mentioned, 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 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 (Robock 2008) recently wrote a paper titled “Twenty Reasons Why Geogenineering May be a Bad Idea.” In that paper he noted 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 middle 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 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. Suppose we implement one of the climate engineering concepts I outlined above to cool the planet in opposition to greenhouse warming. If successful, this cooling will lead to ocean responses on time-scales of decades to perhaps a century. In the mean time suppose we find ourselves in the midst of a period of enhanced volcanic activity. The cooling trend by 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 those concerns, I recommend that major initiatives in climate engineering design using the most advanced models be implemented throughout the world. Before implementation of climate engineering can be done fundamental research is needed to advance our quantitative understanding of the climate system, of climate variability, the scientific possibilities or climate engineering, technical requirements, social impacts, and political structures needed for its implementation. Climate engineering should be considered a “last gasp” measure to prevent catastrophic consequences of a changing climate.

A less learned from cloud seeding that I 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 is in spite of the lack of strong scientific evidence that cloud seeding works. I refer to this as the use of *political placebos*. I anticipate that if we find ourselves in a true climate crisis, that politicians will call for climate engineering measures that will alter the adverse climate trends. If that be the case, let us be sure we do so with the most advanced level of knowledge of the climate system and the full consequences of our actions.

Finally I urge the weather modification community to consider entraining climate engineering into an overall national program in “weather and climate engineering”. I think there may be strong political support to develop a well-funded national program that includes both weather engineering research and climate engineering research. I suggest the best home for such a program would be the Department of Homeland Security or NASA. The two areas of weather engineering that should be given the highest priority are enhancement of water resources in the Colorado River basin and engineering hurricanes. The areas that should be given the highest priority of research in climate engineering is emulating volcanoes in producing long-lasting lower stratospheric aerosols, increasing the albedo of marine stratocumulus clouds, and dissipating cirrus using carbonaceous aerosol seeding .

Acknowledgements: The author would like to acknowledge Brenda Thompson for her assistance with this paper. This material is based upon work supported by the National Science Foundation under Grant No. ATM-0526600. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

5. REFERENCES

Ackerman, A.S., M.P. Kirkpatrick, D.E. Stevens, and O.B. Toon, 2004. The impact of humidity above stratiform clouds on indirect aerosol climate forcing. *Nature*, **432:**1014-1017.

Cotton, W.R., and R.A. Pielke, Sr., 2007. *Human Impacts on Weather and Climate.* Cambridge University Press.

Crutzen, P.J., 2006. Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Climate Change*, **77:**211-219.

DeMott, P.J., M.P. Meyers, W.R. Cotton, 1994. Parameterization and impact of ice initiation processes relevant to numerical model simulations of cirrus clouds. *J. Atmos. Sci*., **41:**77-90.

Durkee, P. A., R. E. Chartier, A. Brown, E. J. Trehubenko, S. D. Rogerson, C. Skupniewicz, and K. E. Nielsen, S. Platnick and M.D. King, 2000: Composite Ship Track Characteristics. *J. Atmos. Sci.,* **57:**2542-2553.

Garstang, M., R. Bruintjes, R. Serafin, H. Orville, B. Boe, W. Cotton and J. Warburton, 2005. Weather Modification: Finding common ground. *Bull. Amer. Meteor. Soc.,* **86:**647-655.

Havens, B. S., J. E. Jiusto, and B. Vonnegut, 1978. Early history of cloud seeding. Project Cirrus Fund, SUNY-ES/328, 1400 Washington Ave., Albany, NY 12203, 75 pp.

IPCC, 2007. *Climate Change 2007 – The physical basis: Working Group I contribution to the fourth assessment report of IPCC*. (Solomon, S.D. et al., eds.) Cambridge University Press, United Kingdom and New York, New York: 996 pp.

Jiang, H., G. Feingold, and W.R. Cotton, 2002. Simulations of aerosol-cloud-dynamical feedbacks resulting from entrainment of aerosol into the marine boundary layer during the Atlantic Stratocumulus Transition Experiment. *J. Geophys. Res*., **107:**4813, doi:10.1029/2001JD001502.

Kärcher, B., O. Möhler, P.J. DeMott, S. Pechtl, and F. Yu, 2007: Insights into the role of soot aerosols in cirrus cloud formation. *Atmos. Res*., **7**:4203-4227.

Latham, J., 1990. Control global warming? *Nature*, **347:**339-340.

Latham, J., 2002. Amelioration of global warming by controlled enhancement of the albedo and longevity of low-level maritime clouds. *Atmos. Sci. Ltrs.*, doi:10.1006/asle.2002.0048

Latham, John, Philip Rasch, Chih-Chieh (Jack) Chen, Laura Kettles, Alan Gadian, Andrew Gettelman, Hugh Morrison, Stephen Salter, 2008. Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Phil. Trans. Roy. Soc.* Submitted.

Lu, M.-L., and J. H. Seinfeld, 2005. Study of the aerosol indirect effect by LES of marine stratocumulus. *J. Atmos. Sci*., **62:**3909-3932.

Minnis, P., J.K. Ayers, R. Palikonda, and D. Phan, 2004. Contrails, cirrus trends, and climate. *J. Climate*, **17:**1671-1685.

NRC (National Research Council) of the National Academy of Sciences, 2003. *Critical Issues in Weather Modification Research*, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, The National Academy Press, 123 pp.

Robock, A., 2008. Twenty Reasons Why Geogenineering May be a Bad Idea. *Bull. Atomic Scientists,* in press.

Watts, R.G., 1997. Engineering response to global climate change: Planning a research and development agenda. CRC Press, Boca Raton, FL: 379-427.