Geo-Engineering the Climate:
Lessons from Purposeful Weather and Climate Modification

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Introduction

An important, though *ad hoc*, "technology assessment"[1] of geo-engineering fixes to the global warming problem is underway. It is a critical effort because the history suggests that, rather early in their evolution, technologies develop path-dependent life cycles and structures and tend to lock in broad sets of social consequences. Of course, the challenge is to assess the likely evolution of a technology and its social framework despite its novel and unique elements. Like other emerging technology, climate geo-engineering takes us into uncharted techno-social territory. But it is also true that humans have attempted to change the weather and the climate for most of human history. Thus one way to cast some light on geo-engineering to mitigate global warming is to analyze the analog: purposeful efforts to modify at least local and regional weather and climate. Purposeful weather and climate modification is not a perfect analog in the sense that it has not sought global effects, but is useful on several counts: (1) past weather and climate modification efforts raised concerns similar to those about geo-engineering, so the analog injects evidence into the current discussion, which is heavy on speculation; (2) weather modification evoked some limited effort among researchers and practitioners to develop standards and guidelines for experimentation and deployment; (3) some of the emerging geo-engineering schemes aimed at global warming (e.g., enhancing oceanic clouds) are versions of more conventional weather modification techniques; and (4) we are likely increasingly to employ orthodox weather and climate modification in response to global warming, so a look back serves even if geo-engineering does not materialize. This paper focuses on lessons for geo-engineering governance from the research on *social dimensions* of weather modification.

Past Efforts at Weather and Climate Modification

As early as 1966, Sewell and Kates framed weather modification as "big science" and argued that: "For 'big science', external criteria are required and the suggested ones are based on considerations of technological merit, scientific merit, and social merit, and are designed to answer the question, why pursue this particular science?" (Sewell and Kates, 1966, p. 351). They were suggesting, in essence, a weather modification technology assessment, which never got done. Now we are asking the question of climate geo-engineering schemes.

Serious efforts have been made in the past century to change the climate of whole regions (the shelter-belt program on the U.S. Great Plain; snow-pack augmentation in the Southwest),

[1] What will be involved in such a technology assessment? One early step should be to look back at previous assessments, a wide range of which were conducted, for example, by the U.S. Office of Technology Assessment during its 23 years of operation up to 1995 (some 750 separate assessments!) available at: http://www.princeton.edu/~ota/ns20/pubs_f.html. Other major assessments were conducted for the super-sonic transport, nuclear power, and anti-missile technology. Typical TAs include a look at: feasibility, cost/benefit, risks, social and environmental impacts (positive and negative), institutional frameworks, ethical dimensions, and alternatives. Less typically, TAs take up the more nuanced issues of opportunity costs and interactions with other options, and factors that tend to narrow the range of choice.

and to routinely alter the meteorology of snow, rain, fog and hail at least locally; we even attempted to modify hurricanes. Weather and climate modification is currently practiced at local to regional scales around the world (Garstang et al., 2005), in dozens, if not hundreds, of operations). Weather modification will surely be ramped up if global warming is perceived as worsening weather- and climate-related problems (e.g., concerns about water supplies in the American Southwest have already evoked increased cloud seeding).

Modern weather and climate modification arose in the last half century based on growing understanding of atmospheric processes; yet it has a checkered scientific history (Committee on the Status and Future Directions in U.S Weather Modification Research and Operations, 2003). Precipitation enhancement has long been the focus, but atmospheric engineering schemes have gone well beyond rainmaking. The Soviet Union in particular advanced large-scale efforts to reduce hail, tornadoes, and drought (Cotton and Pielke, Sr., 1995), and China has a far flung weather modification program today. The United States government has conducted both experimental and operational cloud seeding for various goals, and embarked on an effort to reduce hurricane intensity (Dorst, 2007). Dozens of operational cloud seeding projects are routinely operated in the U.S. by private interests like utilities, state and local governments, and semi-government institutions like taxing districts. Large-scale modification projects (many still in practice) have sought to increase snow-pack in the Rocky Mountains and Sierra Nevada, and rainfall in, for example, Texas, Florida and Dakotas (Garstang, et al. 2005). Some of these efforts, by virtue of their long-term implementation, have ostensibly changed the climate of those places---some stream basins in the Sierra Nevada have been seeded almost every winter for over half a century.

Contemporary weather modification programs rest on a mixture of slender, but encouraging, scientific substantiation and skeptical analysis (Committee on the Status and Future Directions in U.S Weather Modification Research and Operations, 2003) as well as sincere, but also wishful, thinking. The great challenges in weather and climate modification have been to pose a scientifically credible physical mechanism and causal chain yielding the desired results, conduct the project so that the agent and mechanism could theoretically have an effect, and then to measure small effects in a noisy atmosphere. One long-standing criticism of the field (a theme certainly to come up in geo-engineering), is that weather modification projects too often conflate experimental and operational aspects, thus reducing the scientific credibility of results.

Social Dimensions of Weather and Climate Modification

The goal here is not to evaluate cloud seeding science and technology *per se*, but to assess the social response, decision-making, and other implications for geo-engineering governance.

A small and dated, but still useful, body of analysis exists on social response to conventional weather and climate modification schemes, coming especially from sociologists, policy scientists, and geographers (e.g., Steinberg, 2000; Farhar, 1977; Farhar and Mewes, 1975; Sewell, 1966). Fleming's (2007) dismissive *Wilson Quarterly* piece casts past weather and climate modifiers as arrogant "Titans" with no regard for social or environmental consequences. Discussing a 1965 proposal to increase the Earth's albedo with bright particles spread across the tropical oceans (among the first serious global warming geo-engineering schemes), Fleming claims that "No one thought to consider the side effects of particles washing up on tropical beaches or choking marine life, or the negative consequences of redirecting hurricanes, much less other effects beyond our imagination. And no one thought to ask if the local inhabitants would be in favor of such schemes." (p. 58). This criticism is simply not true of many weather and climate modification programs (including hurricane modification, which, I will argue below, was suspended largely due to social concerns).

Social Acceptance

A flurry of peer reviewed studies occurred in the 1970s, when federally-supported weather modification was more common; but a survey of abstracts in the *Weather Modification Journal* (annual publication of the Weather Modification Association, http://www.weathermodification.org/journal.htm) revealed no perception or attitude studies over the last decade, despite the fact that literally dozens of cloud seeding projects operate year after year in many parts of the country. Nevertheless, a small foundation of social science does exist; indeed, I first ran into a sociologist asking people what they thought of cloud seeding in 1971 while I was a student employee on NOAA's Florida Area Cumulus Experiment (FACE; see: Woodley et al., 1977). Admittedly the project meteorologists did not think much of his efforts, believing that simply asking people about the project would bias them against it, but the results (also for Colorado and South Dakota projects) showed strong support for cloud seeding (Haas, 1973). Haas made it a point to interview farmers who voiced concerns about increased rainfall (mostly high-value vegetable growers), and even they mostly supported cloud seeding. Ironically, when I asked sugarcane farmers in the seeding target area what they thought, some said that they already partly controlled the rain by flooding their fields; they were little bothered by the federal government's cloud seeding.

The most well-developed assessment was conducted in the 1970s for hail suppression (Changnon et al., 1978). Extensive surveys and other social analyses found that a majority of the public, especially farmers, believed that the technology could work and that its benefits would outweigh the costs. But the hail studies also asked urbanites what they thought, and explored how cities might deal with extra rainfall (more car accidents). Despite the cloud seeders' expectations that people would imagine all sorts of negative effects, fears about "unintended consequences" and "over-correction" seem to have been relatively mild. Farhar[2] (1975; 1977) specifically examined residents' worst fears, and concluded that the dominant concern in the hail project area was that regular hail suppression would decrease rainfall (i.e., create permanent drought), a sensible worry based in the causal-chain that cloud seeders themselves had presented to locals. A more demanding test of social acceptability came with the 1972 Rapid City flash flood, which occurred amidst a Bureau of Reclamation seeding program was cited by some as causing the flood. Steinberg's (2000) study of the flood's connection (real or imagined) to seeding, based on hearings and reviews by the Bureau of Reclamation, found alarms raised by at least some proportion of the affected population, especially those at risk and those who feel that humans should not try to change nature or interfere in "God's will" (Steinberg, 2000). But Farhar (1976), based on surveys of residents before and after the flood, found that the perceived link between cloud seeding and the flash flood had only a small effect on the strong support her surveys revealed for cloud seeding in the area.

So, there is indeed a history of asking whether "the local inhabitants would be in favor of such schemes," despite Fleming's argument, and the answer, to my reading of the thin literature, is "Yes." The simple persistence today of literally hundreds of cloud seeding projects in the U.S. and elsewhere suggests that despite anecdote and wary cloud seeders, no implacable opposition has emerged. In the U.S. cloud seeding is especially popular in the West, and some dozens of seeding projects have been operated in and around the Colorado River Basin since the 1960s, and

[2] Farhar, as far as I can tell, has more experience studying public acceptance of purposeful weather and climate modification than any other social scientist, and almost all this work was conducted before c.1980. She has made her extensive weather modification files available for further research.

plans are underway for coordinated projects to run for the next quarter century in order to deliver more water to the system (Peterson, 2007). One early project, winter seeding in the San Juan Mountains of SW Colorado (an effort originally under U.S. Bureau of Reclamation's Project Skywater) elicited a series of impact studies and hearings (perhaps the most at the inception of a major modification project); concerns were raised about flooding and avalanche, and placated by a simple criterion: seeding would not occur if snowpacks were above normal (when, of course, it is also less needed). Seeding in the area has run with little overt opposition off-and-on since then, with a hodgepodge of local, federal and private funding. Cloud seeding in Texas is so popular that local tax districts pay for it. Overall, cloud seeding seems to evoke little negative response, and stakeholders from farmers, to skiers, to water managers evince at least the hope that it can help.

In many ways the literature suggests that public perception of routine weather and climate modification leans toward the positive and credulous, perhaps even toward an outsized sense of control over nature, a willingness to accept poorly-supported claims of effectiveness, and a belief that we can change atmospheric systems quite dramatically, and for the better. Various engineering studies, white papers, and agency discussion documents about a renewed, larger seeding effort to enhance runoff in the Colorado River (e.g., Griffith and Solak, 2006) suggest that such optimistic assessments run deep within professional water managers, too. And almost without exception a very positive benefit/cost ratio adheres to, and furthers, cloud seeding: application is relatively cheap compared to the benefits even of an effect (signal) that resides within, or just barely rises above, the noise of weather variability. This applies to everything from snow pack augmentation to hurricane seeding (Sorkin, 1982, p. 95); even a small reduction in wind speed in a hurricane destined to cause billions of dollars of damage would pay off handsomely. Current estimates of additional water in the Colorado River yield benefit/cost ratios of 4-1 to 60-1 (Peterson, 2007).

Finally, cloud seeding is palliative, and called for to fix weather and climate hazards. Cotton (2008), a cloud seeding veteran, finds that weather modification appeals to politicians wishing to "do something" when local economies are threatened by weather problems, and the field's history is full of applied efforts called for by political and business leaders, despite lack of evidence for effectiveness (this occurred in FACE when the governor asked NOAA for operational seeding in the 1971 drought; the scientists were ambivalent but they agreed to seed without case-and-control randomization for two months before the experimental regimen was re-instated (Woodley et al., 1971). Recent hurricane disasters have re-kindled interest in hurricane modification (Department of Homeland Security, 2008).

Liability and Governance

Liability and "robbing-Peter-to-pay-Paul" arguments are common in weather modification discourse, but actual cases simply have not materialized during decades of active cloud seeding. I believe the field has managed to stay in business partly because cloud seeders get to claim a beneficial effect that is small enough not to cause problems. Barely a dozen court cases since 1950 have yielded no findings of liability, nor tort precedence (Standler, 2002, 2006).

Weather modification "governance" is almost non-existent. Professional best-practices and standards do exist, along with a professional society (the Weather Modification Association) and WMO and American Meteorological Society (AMS) policy statements on weather modification and guidelines for projects (http://www.wmo.int/pages/prog/arep/wmp/STATEMENTS/statwme.pdf) and http://www.ametsoc.org/policy/wxmod.html). But, only very weak regulation and government oversight has emerged in cloud seeding projects. Several U.S. states have weak weather modification laws; some have repealed them, or left them un-enforced (Standler, 2002, 2006). The UN general assembly passed in 1977 a resolution proscribing environmental modification as an act of aggression, weaponization, or purposeful harm to another national state, while simultaneously affirming the right of every nation-state to use weather modification to its advantage. The AMS policy statement on weather modification addresses mostly scientific issues, and only lightly suggests attention to liability, compensation, and environmental effects.

Crossing the Line? The Hurricane Exception

Maybe rain and snow augmentation is too tame; perhaps modifying hurricanes is a better analog for climate geo-engineering. Beginning in the 1960s the U.S. experimented with hurricane seeding to reduce storm intensity (Simpson and Simpson, 1966). The social response to Project Stormfury (Dorst, 2007) is poorly recorded (and deserves more digging), but both lay and technical fears were raised, and I believe it fair to conclude that this potentially useful technology was partly stymied, even in the experimental stage, by social and political concerns. Worries included: that hurricanes might intensify and/or change course; that more rainfall would cause worse flooding (a fear founded in the Stormfury's physical logic); and even that tempering hurricanes would affect hemispheric climate by interfering with the poleward transfer of tropical energy. The scientists involved in hurricane seeding tip-toed around such concerns and preferred to keep a low profile (this was mostly before NEPA, EIS's, and public input), but I heard personally from some of the principals that public concerns, media hype, and bureaucratic fears reduced the project's ability to achieve its experimental goals. Some of this frustration peeks through in the Dorst (2007) history of Stormfury, and in biographies of those involved, see, for example: http://earthobservatory.nasa.gov/Features/Simpson/simpson.php (I worked as a student employee for Joanne Simpson in 1971-73 when she had turned from hurricanes to seeding individual clouds over Florida.)

In "The Decision to Seed Hurricanes", a classic early quantitative risk analysis still used in risk assessment classes today, Howard et al. (1972) raised concerns about "responsibility costs," the notion that once the government (or any institution or persons) seeds a hurricane, it then "owns" the damage done by that storm, at least the damage above some baseline level that would have occurred naturally, a level notoriously difficult to assess. They even suggested that given the large value of hurricane losses (even then, before we had multi-billion dollar storms), that the responsibility costs might be so large as to preclude ever seeding a storm. *They concluded that perhaps only emergency seeding in the face of catastrophic storms would override this threshold.*

Cautionary rules developed for when hurricanes could be seeded (derived from precisely the kind of concerns for unintended consequences that Fleming claims have been ignored) so constrained the experimental area in the Atlantic Ocean that opportunities to seed storms failed to materialize (figure 1). Efforts to shift the program to the more active Pacific were thwarted by logistics and the expressed concerns of some Pacific Rim countries, a foreshadowing perhaps of the geo-politics of geo-engineering. No detailed history of this effort has been written to my knowledge, but by most accounts China, Japan and Australia all raised concerns. Japan meteorologists suggested that typhoon seeding might rob the country of needed rainfall (Fitzpatrick, 2006), and China's dissent was wrapped up in its belief that seeding of the Ho Chi-Minh Trail during the Viet Nam War had actually caused enough additional rainfall to slow movement, and thus represented a potent technology that could negatively affect continental rainfall patterns (List 2004).

Ultimately, Stormfury seeded only four storms in 21 years, a run that sapped its enthusiasm, and, finally, its funding in 1983 (Dorst, 2007). Concerns about the unintended consequences of hurricane seeding were one factor in the project's failure. But Stormfury offers another cautionary tale for geo-engineering. The research associated with it, including much better hurricane monitoring, showed that hurricane clouds were not good candidates for a seeding effect based on freezing nuclei, and revealed the episodic intensity changes (especially eye-wall replacement cycles) that to this day still bedevil hurricane forecasting. The more they learned, the more that Stromfury researchers realized how hard it would be to demonstrate an effect (Willoughby et al., 1985). By the same token they realized that they could not constrain their potential responsibility in a seeded hurricane disaster, but there's no record of how much this realization affected the project's feasibility.

So the history of weather modification offers a mixed message. Routine cloud seeding for more rain and snow is permissible, even desired, and practiced with little regard to liabilities or demonstrated effectiveness year after year in the U.S. and around the world: if it works, then the climate of those places has, indeed, already been changed. Yet the arguably more vital, but spookier, effort to modify hurricanes was, ultimately, impermissible, and ran aground on fears of unintended consequences, political sensitivities, and the *a priori* likely under-determination of its effectiveness.

Some Implications for Geo-Engineering

Purposeful weather modification is an imperfect analog to geo-engineering, but does offer some lessons. Like weather modification, geo-engineering offers rather large assumed benefits compared to costs. Cost-effectiveness calculations made by the Committee on Science Engineering and Public Policy, (1992, p. 486) or COSEPUP study two decades ago, though rough, seem in line with recent estimates (Robock et al., 2009), and yield attractive numbers. Of course the costs and benefits will not be evenly distributed. Cloud seeders have long worried about creating losers, even though there is only null experience in weather and climate modification liability so far. And certainly similar concerns attach to geo-engineering. Evidence that stratospheric aerosols might reduce the South Asian Monsoon raise the specter of potential harm to especially vulnerable populations. Schneider (2008) even suggested that the aggregate climate change (cooling plus warming) across the globe might be *increased* by geo-engineering schemes that nevertheless achieve their goal of cooling global mean temperature, suggesting that losers might be legion even in an effective program.

Still, the appeal is similar: geo-engineering offers an alternative if others fail and/or if climate change is worse than we think. Go-engineering schemes are often described as a last resort, and as emergency measures (The Royal Society, 2009). The American Meteorological Society's (AMS) (2009) policy statement on geo-engineering picks up on this theme: "Geoengineering could conceivably offer targeted and fast-acting options to reduce acute climate impacts and provide strategies of last resort if abrupt, catastrophic, or otherwise unacceptable climate change impacts become unavoidable by other means."

Realized global warming is also likely to elicit more conventional local and regional weather modification, including especially precipitation enhancement and, maybe, hurricane modification, so a geo-engineering technology assessment might also address traditional weather modification writ larger. It also works out that, despite much attention to novel schemes like stratospheric aerosol injection, many anti-global warming schemes are based on more conventional weather modification techniques, including seeding to change the albedo of naturally-extensive cloud systems like oceanic strato-cumulus (ships already enhance oceanic clouds from their stack effluent) (Cotton, 2008; Latham et al., 2008). Since cloud seeding is currently conducted on a routine basis in many places in the U.S. and around the world, without discernible negative effects or significant social opposition (Cotton and Pielke, 1995; Garstang et al., 2005), it would seem that geo-engineering schemes that emulate past weather modification seem more likely to advance to field trials than others. But the Project Stormfury experience does suggest bigger hurdles for bigger projects, and my hunch is that large-scale geo-engineering will run afoul of the same frustration: field tests are so constrained that they become infeasible.

The AMS policy statement on geo-engineering calls for: "Development and analysis of policy options to promote transparency and international cooperation in exploring geo-engineering options along with restrictions on reckless efforts to manipulate the climate system." We are a long way from this level of governance, even for conventional weather and climate modification, and again the Stormfury experience suggests potential benefits of getting mechanisms in place to sort out risks and benefits and to achieve acceptance, if it is to be had, of field trials.

One other lesson from cloud seeding is the tendency for projects to be pushed form experimental to operational deployment. As research funding for cloud seeding declined, scientists could not help but be attracted to operational programs in the hope that they could still practice good science while trying simultaneously to delver more rain or less hail (or both) to, say, farmers in Texas and the Dakotas. I'm not competent to judge how this has turned out but the apparent conflict of interest inherent in such an approach is surely something to be avoided in geo-engineering research.

A Global "Levee Effect"?

Some discussions of geo-engineering suggest that such potential fixes of global warming would reduce the pressure for reductions in GHG emissions, and that even analyzing engineering solutions puts us on a slippery slope to relying on them instead of mitigation (e.g., Kiehl, 2006; Fleming, 2008; Robock, 2008; The Royal Society, 2009). It might be that the tendency of cloud seeding projects to slip into operational mode is a signal of this effect.

The thinking goes that serious attention to climate-cooling schemes might invoke the "moral hazard" behavior presumably associated with some forms of insurance (i.e., the insured can afford to take larger risks that could endanger others, including uninsured parties). But perhaps geo-engineering is more akin to the paradox that natural hazards researchers call the "levee effect": i.e., that dams and levees create a sense of security and encourage flood zone development, thus exacerbating future losses when inevitable failures occur, also known as the "safe development paradox." (Burby, 2006).

It is easy to speculate, to attribute behavioral modes to the entire human population, but more difficult to prove those behaviors are universal or likely to emerge in any given situation. I think this is also true of the moral hazard argument; quite simply, it is difficult to sustain or refute, party because its proponents have not demonstrated its real-world effects in analog cases or with empirical evidence. The question of whether insurance and/or disaster relief encourage risky behavior has not been settled after years of debate among hazards researchers, suggesting to me that the effect is not very strong. Mileti (1999) concludes that expectations of relief do not necessarily encourage hazard zone occupance, but insurance might. Kunreuther, the leading scholar of hazards insurance concluded after Hurricane Katrina that expectations of government aid do indeed reduce adoption of both pre-hazard mitigation and of insurance (Kunreuther, 2006). But he also concludes that insurance can be, and often is, designed to block moral hazard: insurance companies have a hook to enforce mitigation (e.g., increased premiums for risky behavior, and discounts for risk reduction behavior) and relief rarely compensates for all losses, so the logical homeowner, for instance, does not use either as an excuse to ignore or to invoke risks.

No hint of a moral hazard shows up in the weather modification literature, and no evidence it changes the behavior of resource managers or other stakeholders. In a recent severe drought, Denver Water Board paid to have parts of its watersheds seeded, but it and associated utilities (including my water provider, the City of Boulder) also formally declared a shortage and invoked water use restrictions based on system performance criteria that include no assumed benefit from seeding (and I got a $60 fine for watering my grass on the wrong day of the week—no moral hazard there!).

On the other hand, there is some evidence for the "levee effect" whereby levees and dams invite development that then incurs even greater losses when they fail; they do not just invite development in floodplains, that is what they are designed to do, but that they in some cases increase net losses (Burby, 2006; Kates et al., 2006). The levee effect is not quite analogous to a moral hazard, but it may inform our thinking about geo-engineering. For example, maybe the risk is not so much that the geo-engineering prospect squelches mitigation, but that it would dampen adaptation.

A similar argument was raised against research on adaptation to climate change, which could also be seen as dampening efforts to reduce greenhouse gases. Critics argued that the adaptation sub-panel of the Panel on Policy Implications of Greenhouse Warming (COSEPUP, 1992) was over-optimistic about the potential for social adaptation to global warming. Two panelists wrote dissenting statements to this effect (pp. 84-84, and p. 659).[3] I believe we have usefully gotten past the argument that research on adaptation is counter-productive (because both mitigating and adaptation appear necessary), but the debate over geo-engineering opens up lots of room for similar arguments.

Conclusions

The few *a priori* guidelines thus far offered for assessing the feasibility and desirability of geo-engineering (Jamieson, 1996; Sarewitz and Nelson, 2009) would appear to tender very high theoretical hurdles. Yet technologies in use today to change the weather and climate at least locally, including routine cloud seeding, would not meet such criteria but are in widespread use. On the other hand, seeding to modify hurricanes appears to have foundered on the rocks of both concern for unintended consequences and of a deep uncertainty that the beneficial effect could be unambiguously detected. Recent studies suggest that the latter problem might not be as great for some geo-engineering schemes (Robock et al., 2009) and the history of weather modification suggests a range of acceptability in which some geo-engineering field trials (e.g., oceanic cloud modification) could proceed quite readily, while other approaches (e.g., stratospheric aerosols) would require much more analysis and assessment, as well as a concerted effort to create a governance structure that could not only support research and testing (and maybe even deployment), but be counted on to keep experimental efforts from morphing into operational ones, and to chart a regulatory framework that could veto dangerous climate interventions while simultaneously avoiding the rejection of a beneficial techniques.

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[3] I was a member of the panel, under my previous name, William E. Riebsame.

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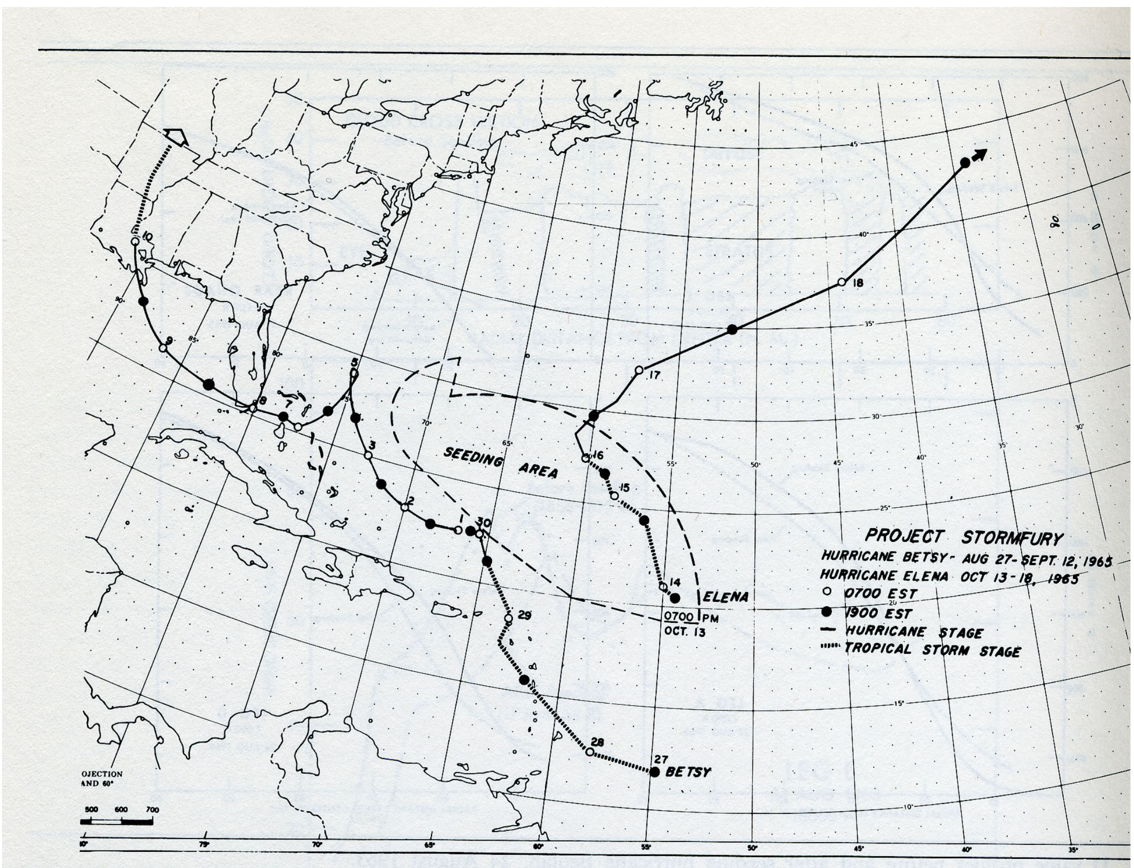

Fig 1: The experimental area for Stormfury (shown here in its first season when the two storms with the most potential seemed to avoid it) was too limited to provide many seeding opportunities; lack of storms in the right area at the right intensity and operational readiness conspired to limit Stormfury to two seeding efforts after the constraints were put in place and these produce unsatisfactory results. From: Simpson and Simpson, 1966.