Using Twentieth-Century U.S. Weather Modification Policy to Gain Insight into Global Climate Remediation Governance Issues

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ABSTRACT

With atmospheric greenhouse gas concentrations increasing and binding agreements to reduce anthropogenic emissions wanting, interest in geoengineering as a climate remediation option to be used in tandem with climate change mitigation is growing. Solar radiation management (SRM), due to its relatively low financial cost and the potential for near-term reduction in average global temperature, is gaining particular attention despite the risks of its use, both identified and unanticipated. This paper considers the structure—the participants, positions, actions, outcomes, information, and positive and negative payoffs—of U.S. weather modification research and governance developed between 1947 and 1980, offering a case study that may be useful in thinking through how to move forward with SRM development and governance should a decision be made to contemplate augmenting mitigation and adaptation with geoengineering.

1. Introduction

Geoengineering refers to the deliberate manipulation of the earth's climate system to reduce the effects of human-made climate change (Keith 2000; Cicerone 2006; Crutzen 2006; MacCracken 2006; Schneider 2008). Geoengineering methods are typically categorized as either carbon dioxide removal (CDR) or solar radiation management (SRM) techniques. The former includes processes to remove carbon from the atmosphere, while the latter describes techniques to reduce incoming solar radiation to lower average planetary temperature. CDR techniques tend to be less risky than SRM but are more expensive to implement and slower acting, with technological CDR solutions still in development (Shepherd et al. 2009; Russell et al. 2012). Of the two, SRM attracts particular attention because of the speed at which it could lower global temperature (Crutzen 2006; Wigley 2006) and its relatively low financial costs as compared to the expense of greenhouse gas (GHG) mitigation (Barrett 2008; Keith et al. 2010); this paper focuses largely on SRM. Given the global inaction on climate change mitigation, geoengineering may come to be perceived as a serious option in a climate emergency; that is, if a climate catastrophe that would cause widespread and sudden harm seems imminent (Gardiner 2011). Its use could also potentially ameliorate some of the adverse effects of climate change as society implements GHG mitigation and adaptation strategies (Crutzen 2006).

If SRM is to become a potential complement to global mitigation and adaptation efforts, a framework of rules and regulations is likely to be essential before experimental development or actual implementation goes forward, given the broad range of potential environmental, technical, political, and ethical benefits and harms of SRM (Rayner et al. 2009; Shepherd et al. 2009; ASOC 2010). In this paper, the term "governance structure" is intended to encompass participants, positions, values, information, actions, outcomes, the functions linking actions and outcomes, and any positive and negative payoffs associated with the potential activity (Ostrom 1999; Folke et al. 2005; SRMGI 2011).

At this time, a governance framework does not exist either for SRM specifically or for geoengineering in general. In considering what governance might be needed to carry forward a potential geoengineering development and deployment effort, weather modification governance may offer a useful proxy, as it is a technology similar to SRM and is undertaken and governed at

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national and subnational levels in dozens of countries (WMO 2007). In particular, weather modification involves human-driven efforts to influence atmospheric processes that compose the weather on local scales through use of cloud seeding (U.S. Department of Commerce 1979). While similar in that each has the goal of intentionally influencing atmospheric processes, weather modification and SRM differ in terms of temporal and geographic scales. Weather modification effects generally last for hours and occur over geographic scales of tens of kilometers; SRM effects last for weeks to years and occur over hundreds of kilometers to planetary scales, potentially causing environmental and societal influences that would persist long after an effort was ended.

In practice, weather modification can be broken into two categories: experimental and operational. Experimental efforts are those in which researchers and agencies strive to ascertain the effectiveness of weather modification applications through rigidly controlled tests to determine whether desired results (e.g., precipitation enhancement) are achieved at the earth's surface. Operational programs apply cloud seeding techniques to maximize the desired weather modification results (U.S. Department of Commerce 1979). Such operational programs assume some level of efficacy for altering the weather, but few scientifically evaluate project outcomes to test their assumptions (WMO 2007).

Looking at U.S. federal weather modification governance as an analog for SRM governance

In this paper, U.S. federal weather modification governance developed between 1947 and 1980 (the period of peak federal funding) is used as an SRM governance proxy. While U.S. weather modification efforts represent only one example of the world's weather control programs, it is the focus here because of the relatively long program history and because it offers well-documented analyses of program structure, outcomes, and future requirements (see Table 1). Weather modification projects have run continuously since the 1950s in several U.S. states; consideration of North Dakota's weather modification program and its governance structure is compared to that of federal programs to assess possible governance components contributing to program longevity. Weather modification programs run in other nations are not considered; however, a review of such programs may offer additional insights from which geoengineering governance creation will benefit.

Through the rest of the paper, I advance some of the arguments addressing the need for SRM research and present the parallels between weather modification and geoengineering and the evolution of federal weather modification governance. Focus is more on structure (i.e., the various components of the governance system), rather than specifics on content (i.e., details on governance rules and guidelines). I consider how "good" weather modification governance might have been structured; explore the reasons why U.S. federal weather modification governance did not fully realize its potential and why state-level weather modification has fared better; and suggest some lessons learned from weather modification that might be useful to consider if moving forward with SRM development and, potentially, deployment.

2. Similarities in consideration of governance for weather modification and SRM

Studying a proxy technology such as weather modification and its related governance structure has the potential to provide an initial template for action and insights into possible repercussions, downstream impacts, and societal reaction to advancing an SRM option. While the match as a proxy to geoengineering is not perfect, many of the weather modification issues that lawmakers and scientists struggled with between 1947 and 1980 are similar to those already arising in today's early discussions of climate engineering benefits and conundrums (see Table 2).

a. SRM and weather modification similarities: Addressing societal issues

Observational evidence shows that many natural systems are being affected by regional climate changes (Alley et al. 2007). Rising global average temperature, a predominant climate change feature, is associated with a variety of other climatic impacts, including impacts affecting ecosystems and water resources at local, regional, and global scales (Alley et al. 2007). Based on detection and attribution analyses, the observed increases in global average temperatures occurring since the mid-twentieth century have been convincingly linked to observed increases in anthropogenically increased GHG concentrations (Hegerl et al. 2007). With global GHG concentrations expected to continue to increase, warming and global climate system changes will continue throughout the twenty-first century (Alley et al. 2007) even if atmospheric CO_2 emission levels are stabilized in the near term (Matthews and Caldeira 2008; Friedlingstein et al. 2011).

To stabilize the climate, emissions must be brought down sharply, which will require comprehensive global cooperation. While some nations such as Japan, Norway, and Germany have had success in their efforts to reduce their global emissions, the current pledges for reductions in national emissions are insufficient to meet

TABLE 1. Components of U.S. weather modification governance.

Institutions	Federal agencies (e.g., NSF, NOAA, Department of Commerce) Congress/legislative branch White House/executive branch ICAS Private industry (e.g., General Electric) U.S. courts ACWC
Authority/actors	Congress: Had authority but necessarily focused on a range of national problems; interest in weather modification arose in reaction to problems that the technology might solve (e.g., western water issues, the race for scientific supremacy over the Soviet Union). White House: Like Congress, the White House had governance authority but used it reactively to address national issues that weather modification technology or knowledge might have solved. NSF: Advised by the ACWC, Congress gave NSF a leadership role in weather modification in 1958; NSF's mandate to fund basic scientific research to expand knowledge for societal benefit did not fit well with congressional desires to apply weather modification techniques to address societal problems. Congress removed the leadership role for weather modification from NSF in 1968. ICAS: Established by the White House based on an NSF recommendation in 1959 to coordinate cross-agency weather modification programs, the ICAS and NSF coordination responsibilities overlapped, allowing agencies to bypass the authority of both organizations. U.S. Department of Commerce: Responsible for collecting information on U.S. weather modification projects; had little effective authority beyond data collection. Private industry: Might have played a role in governance through varying degrees of standard setting, implementation, and enforcement (Freeman 2000); however, smaller private firms tended to be the ones involved in weather modification, which likely limited the impact of industry on weather modification governance. U.S. Courts: Courts offer a means of elaborating upon and enforcing social norms through adjudication processes and in doing so influencing governance mechanisms (Scott and Sturm 2006). Because most weather modification experiments were classified by the military or run in applied modes, courts had no basis for making rulings on weather modification cases and therefore did not influence governance.
Rules	Eight U.S. public laws related to U.S. weather modification (see Table 2) Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD Convention) was designed to establish limits on use of the environment as a weapon or an instrument of military operations; the United States ratified ENMOD in 1980. U.S.–Canada Agreement Relating to the Exchange of Information on Weather Modification Activities: A 1975 agreement between the United States and Canada in which each nation promised to inform the other of the nature and extent of weather modification activities that might have transboundary effects.
Values driving weather modification use	U.S.–Soviet competition for scientific superiority and Cold War fears. Fear of the global spread of communism (e.g., Vietnam War). Societal benefits: For example, ensuring adequate water to meet projected demands of a growing U.S. West population, reducing deleterious effects of weather extremes on society (e.g., drought, costs due to severe weather such as hurricanes, hail damage to crops, or effects of fog on air transportation that might affect flight safety or schedules). Satisfaction gained from gaining the upper hand over weather and advancing a technology that would benefit society.

the objective of keeping global average warming below 2°C (Rogelj et al. 2010). Moreover, even in cases where nations are committed to reducing emissions, the likelihood of meeting targets appears to be low (Pielke 2009a,b, 2011). These realities and growing concerns about accelerated warming (e.g., as a result of significant methane emissions from thawing permafrost) have led some to suggest that the world would benefit from pursuit of SRM research. Not least, research may establish whether it is even feasible to use SRM to restrain global warming concurrently with global mitigation and adaptation efforts (Blackstock et al. 2009; Caldeira and Keith 2010; Keith et al. 2010; Task Force on Climate Remediation Research 2011).

Similar to geoengineering, cloud seeding techniques were explored beginning in the 1940s as a means for humans to moderate extreme weather, with the intent being, as appropriate to the situation, to augment or suppress rain or snow, hail, fog, lightning, or severe storms so as to reduce loss of human life and injurious societal impacts. Vincent Schaefer's 1946 discovery that ice crystals can form in high humidity environments

TABLE 2. Similarities between U.S. weather modification and solar radiation management.

	Solar radiation management	Weather modification (1947–80)
Potential societal benefits	SRM may provide a fast, affordable means of reducing or limiting impacts resulting from the ongoing increase in global average temperature.	Weather modification offered the promise of reducing deleterious effects of local weather events such as fog, hail, or hurricanes, along with benefits from increased precipitation over agricultural or arid regions.
Concerns about technology use	In addition to intended benefits, deployment of, and possibly even research on SRM could lead to a variety of unknown and unintended outcomes that have the potential to leave the environment or society less well off than before (Shepherd et al. 2009). An assessment of the risks and benefits of pursuing geoengineering research vs not doing so will be important (Task Force on Climate Remediation Research 2011).	Weather modification suffered from similar concerns as those expressed for SRM (i.e., unknown and unintended consequences, adverse public reaction to technology use); however, this was especially worrisome for decision makers and researchers with regard to large-scale phenomena such as hurricanes (Travis 2010).
	Done in an unconfined area that cannot be controlled, effects will likely extend beyond intended boundaries, potentially crossing state or national borders; understanding the significance of such effects will be important (Shepherd et al. 2009; U.S. GAO 2011; SRMGI 2011).	Done in an unconfined area that cannot be controlled, weather modification effects had the potential to extend to beyond intended boundaries, potentially crossing state or national borders (CRS 2004).
	Given the complexity of the atmospheric system and the variety of scientific unknowns, attribution of natural variability or human interference will likely be difficult to establish definitively for SRM (SRMGI 2011).	Given the complexity of the atmospheric system and the variety of scientific unknowns, attribution of natural variability or human interference was difficult to establish definitively (NRC 2003).
Considering the technology and the public good	Many feel that to ensure transparency and maximize use of geoengineering for the greatest public good, research and research outcomes must remain within the public domain (Victor et al. 2009). Concern exists that patents filed related to fundamental SRM technology may impede research transparency; in addition to the possibility of causing geopolitical tension by concealing some aspects of research, use of patented technology may lead to inappropriate testing and deployment or result in a commercial entity having too much influence on the direction of SRM research and development (Olson 2012).	In the case of weather modification use and the public good, decision makers questioned the validity of claims of environmental remediation made by a growing number of private cloud seeding organizations; this led to a call for improved scientific understanding of weather modification's capabilities (Lambright 1972; CRS 2004).
Including the public in the decision process	If global SRM research or deployment goes forward, much of the global public may be affected by these efforts either directly (e.g., due to changes in local weather or climate) or indirectly (e.g., shifts in prices due to weather or climate changes). Because of these impacts, public understanding of and input on geoengineering risks and rewards will be important (Rayner et al. 2009).	In the case of weather modification, public input might have benefitted the federal weather modification program; however, fear of negative public reaction on the part of decision makers (Haas 1973) likely reduced communication efforts and broad sharing of weather modification information.
	In the case of SRM and geoengineering public opposition to research has already halted ocean fertilization research (Hale and Dilling 2011).	
	Public advocacy groups contributed to halting a recent SRM experiment, the U.K. Stratospheric Particle Injection for Climate Engineering (SPICE) project (Cressey 2012).	
Human hubris	Disquiet related to the hubris of humans seeming to "play God" (Fleming 2007; Victor et al. 2009; Gardiner 2010; Keith et al. 2010).	Disquiet related to the hubris of humans "playing God" (Haas 1973).

(e.g., clouds) and act as condensation nuclei opened up the potential for weather modification. Working at General Electric (GE) in Nobel Prize winner Irving Langmuir's laboratory along with Schaefer, Bernard Vonnegut obtained a similar result to Schaefer's by seeding clouds with silver iodide in 1947 (NRC 2003; Cotton and Pielke 2007; Fleming 2010). Research building on these discoveries more than 60 yr ago led to the weather modification programs that are currently being operated in many countries where limited water resources restrict food and energy production (WMO 2007).

b. *SRM and weather modification similarities: Dealing with the scientific uncertainties*

While SRM has the potential to offer a fast-acting, affordable option in a climate emergency, the implications of using SRM will merit careful consideration before implementation (Crutzen 2006; Wigley 2006; Shepherd et al. 2009; Victor et al. 2009; ASOC 2010; Blackstock and Long 2010; MacCracken 2010; SRMGI 2011; Task Force on Climate Remediation Research 2011). Because of the complexity of the atmospheric system, use of some SRM techniques may result in both benefits and adverse effects; these would vary based on the technique employed. For example, rooftop whitening seems likely to be a comparatively benign SRM technique, while studies indicate that stratospheric aerosol loading may interfere with monsoon patterns, reduce precipitation, cause hazy skies, or reduce stratospheric ozone (Crutzen 2006; Fleming 2007; Robock 2008a,b; Barrett 2008; Blackstock et al. 2009; Blackstock and Long 2010; Keith et al. 2010). At this point, however, it is difficult to clearly determine all of the possible effects, much less unambiguously identify which of these will be adverse or beneficial and how pronounced such effects might be.

In addition, SRM research and deployment, whether prospective or actual, seem likely to raise a variety of ethical issues. For example, the potential success of SRM might reduce the pressure to lower emissions, thus imposing greater obligations and impacts on future generations. As another example, no procedures are currently in place to gain international governmental and public consensus—particularly consensus that would include the most vulnerable or affected—on where to set the global thermostat if SRM were to become possible.

c. *SRM and weather modification similarities: A need to address decision making, cross-institutional communication, and funding-related issues*

Weather modification governance between 1947 and 1980 appears to have been created reactively and haphazardly in response to the tenor and clamor of the times, rather than deliberately. In the early 1950s, the U.S. federal government spent $3–$5 million annually to fund federal agencies, universities, and private companies to run weather modification projects (CRS 2004). Between 1950 and 1956, application of these emerging capabilities occurred, on average, across 10% of the national landscape (Lambright 1972; CRS 2004). The geographical extent of these efforts generated apprehension that effects would extend beyond intended boundaries, potentially crossing state and even national borders (CRS 2004). These concerns led Congress to enact Public Law 83-256, which led to the creation of the Advisory Committee on Weather Control (ACWC) in August 1953 (see Table 3 for a list of weather modification-related public laws). The ACWC was tasked with assessing public and private weather modification efforts and gauging related research benefits and needs. ACWC membership included scientists, politicians, and businessmen, with equal representation between government and nongovernment entities as an attempt to balance differing and possibly competing interests (CRS 2004).

During the time that the ACWC was assessing weather modification research, U.S.–Soviet tensions and a competition between the two nations to gain the upper hand in scientific understanding increased federal decision makers' focus on the nation's science needs and capabilities (NSF 1959; Wollan 1968). This reality, combined with a recommendation from the ACWC, led Congress to pass an amendment in 1958 to the National Science Foundation (NSF) Act of 1950 (Public Law 85-510). Public Law 85-510 expanded NSF's long-range program of basic and applied research to include study, research, and evaluation of weather modification; this program was expected to run in cooperation with other agencies (NSF 1959; CRS 2004).

During the 1950s and 1960s, the arid U.S. West was experiencing significant population growth. U.S. congressional representatives hoped that enhancing precipitation could provide the water needed to sustain and increase societal and economic benefits. Two National Research Council (NRC) reports (NAS-NRC 1964, 1966a,b) buoyed these expectations. While the 1964 report was equivocal about the ability of weather modification techniques to generate environmental change for societal benefit, the 1966 report suggested that the latest evidence indicated modest improvements in precipitation formation in some cloud types after weather modification. With the 1966 findings superseding those of the earlier report, weather modification programs benefited from funding increases; Congress boosted weather modification support from $4.97 million in fiscal year 1965 (FY65) to $9.92 million by FY67 (CRS 2004).

TABLE 3. The eight federal laws created during the 30-yr U.S. federal weather modification program.

Public Laws 83-256 and 84-664	As the number of experiments grew, concern over cross-border (state and national) effects led to the establishment of the Advisory Committee on Weather Control (ACWC) with Public Law 83-256 in August 1953. The ACWC was created to assess public and private weather modification experiments; Public Law 84-664 (July 1956) extended the period of ACWC operation to 1958.
Public Law 85-510	Public Law 85-510 (July 1958) made the NSF the official agency for coordinating research projects. NSF was to become the central point for assembly, evaluation, and dissemination of information about weather modification. NSF's mandate included providing public access to research results. No requirement of research–result assessment was made of NSF beyond archiving records of weather modification activities and reporting annually on federal programs and the general status of the field.
Public Law 87-330	Public Law 87-330 (September 1961) had a broader public works focus; through a $100,000 earmark, Congress initiated Project Skywater, an atmospheric water resources program run by the Bureau of Reclamation in the U.S. Department of Interior. Unlike other weather modification laws, this one benefitted from ongoing congressional direction and funding that extended beyond 1980. The goal of Project Skywater was to develop and verify a practical cloud seeding technology for increasing water supplies in the U.S. West through research and development done by universities, research centers, and industry.
Public Law 90-407	Although not exclusively concerned with weather modification, section 11 of Public Law 90-407 (July 1968) repealed Public Law 85-510, thereby taking away NSF's lead agency role.
Public Laws 92-205 and 93-436	Public Law 92-205 (December 1971) required reporting to the federal government via the U.S. Department of Commerce by ''. . .any individual, corporation, company, association, firm, partnership, society, joint stock company, any state or local government or any agency thereof, or any other organization, whether commercial or nonprofit, performing weather modification activities, except where acting solely as an employee, agent, or independent contractor of the Federal Government.'' Public Law 93-436 (October 1974) extended authorization of a $200,000 earmark to fund the Department of Commerce to carry out Public Law 92-205 through 1977.
Public Law 94-490	Public Law 94-490, 13 Oct 1976, authorized the Secretary of Commerce to develop a national policy on weather modification and to extend appropriation authorization for reporting and disseminating weather modification activities, as prescribed by Public Law 92-205 through 1980.

However, throughout NSF's tenure, an inherent disconnect existed between NSF's understanding of its function and Congress's view of the NSF mission. NSF saw its role as supporting basic (experimental) research on weather modification. Congress, however, saw the agency as having responsibility for advancing application of technologies that could aid U.S. public needs and compete with supposed Russian innovations in this area (Wollan 1968). This difference in understanding of the NSF mission caused an abbreviated and often powerless tenure for NSF as the lead agency in U.S. weather modification. The difference in perspectives also led Congress to target more funds to non-NSF agencies, notably the Department of Interior's (DoI) Bureau of Reclamation, to develop and carry out desired operational weather modification missions (Wollan 1968; Lambright 1972).

By 1968, Congress made its dissatisfaction with NSF official; an amendment to the NSF act terminated NSF's role as lead agency for weather modification with Public Law 90-407 (CRS 2004). However, even without a lead agency, federal weather modification funding continued to increase steadily between FY63 and FY73 (CRS 2004). As of FY71, six federal agencies [DoI Bureau of Reclamation, NSF, National Oceanic and Atmospheric Administration (NOAA), Department of Defense, U.S. Department of Agriculture/Forest Service, and National Aeronautics and Space Administration (NASA)] received more than $15 million to support various weather modification efforts, most being operational in nature (Lambright 1972).

In addition to leadership issues occurring during the 10 yr when NSF acted as lead agency for federal weather modification, interagency communication proved problematic. The Interdepartmental Committee for Atmospheric Sciences (ICAS), established by the White House based on an NSF recommendation in 1959, ostensibly coordinated interagency weather modification programs. However, the dual existence of NSF and ICAS allowed the various funded agencies to pursue their own particular weather modification projects and to evade research-coordination efforts. Further complicating the issue, different congressional committees governed the various agency departments receiving weather modification funds; these committees did not, however, generally coordinate with each other.

d. SRM and weather modification similarities: Concern about private and military interests and technology use

Concern has been raised that a nation or a ''greenfinger''—an individual or organization with the money and interest to pursue geoengineering—might unilaterally deploy SRM technologies for purposes other than the general public good (Victor et al. 2009; Keith et al. 2010). Some of this concern likely stems from Operation Popeye, a covert U.S. military effort that perhaps had the most significant influence on public perceptions about weather modification, making it an important influence on federal-level decisions and governance.

The U.S. Department of Defense (DoD) conducted Operation Popeye between 1967 and 1972 in hopes of increasing monsoon rains in Southeast Asia to hinder transport by the North Vietnamese army over the Ho Chi Minh Trail, a main supply line (U.S. Senate Subcommittee on Oceans and International Environment 1974). Not run in a manner to allow evaluation of effectiveness, this effort added little to the understanding of weather modification efficacy but did incite global concern about military use of weather modification and other technologies that might lead to manipulation of the environment for malevolent purposes (UN 1976). The United Nations Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques [shortened to the Environmental Modification Convention (ENMOD)] resulted from this concern. In addition, perhaps fueled by early leaks to the press of the Operation Popeye controversy, Congress renewed its interest in agency oversight in 1971; Public Law 92-205 tasked the Department of Commerce with monitoring U.S. weather modification efforts, making reporting of weather modification programs to a federal authority a requirement.

Fallout from Operation Popeye, the lack of agency leadership, insufficient proof of weather modification efficacy, and poor communication and collaboration across agencies (Weather Modification Advisory Board 1978; U.S. Department of Commerce 1979) contributed to a decrease in federal funding for weather modification in the late 1970s; federal funding effectively ended in 1980 with Reagan administration cutbacks (Lambright and Changnon 1989).

e. SRM and weather modification similarities: Ethical dilemmas for SRM and weather modification and the state of public input

The U.S. experience with weather modification raised ethical concerns similar to those arising in early consideration of SRM. For example, apprehension exists that SRM will result in nations continuing business as usual rather than reducing emissions and that deployment will be an inevitable outcome of starting research and there is concern that future generations and the most vulnerable and voiceless populations will be excluded from or overlooked in SRM-related decisions. Added to these concerns is the notion of the hubris that encourages humans to ''play God'' with the climate system (Fleming 2007; Joronen et al. 2011). As the Royal Society's SRMGI (2011) authors point out, humans have inadvertently interfered with the global climate on a large scale for centuries, but deliberate interference with natural systems on a planetary scale offers a distinct moral contrast.

The weather modification analog suggests that it may be more difficult than imagined to forecast societal reaction to SRM. Since the 1960s, hundreds of weather modification projects have been carried out in the United States, and regionally or state funded operational projects continue today (Travis 2010). For the vast majority of the federally funded projects occurring between 1947 and 1980, no resistance developed to weather modification (Haas 1973; Travis 2010). In fact, evidence shows the public was largely supportive of or ambivalent about use of weather modification until Operation Popeye (Haas 1973; Farhar 1974; U.S. Senate Subcommittee on Oceans and International Environment 1974; UN 1976; Changnon et al. 1978: Lambright and Changnon 1989; Travis 2010). This relative lack of concern may have resulted because of the limited temporal and geographic scales of weather modification efforts before that time and perhaps indicates a level of confidence in the program's scientific and technological capabilities.

In terms of public perception of weather modification, Haas (1973) studied the context and public response to three weather modification projects. He found that those paying for weather modification efforts through their taxes but receiving no direct benefit often favored weather modification, seeing it as a worthwhile risk even while expressing some misgiving relating to pitting human powers against nature (Davis 1974). That said, Haas also found that, where concerns existed, groups expressing opposition were generally more powerful in terms of political influence. Not surprisingly, this proved especially true for publicly funded projects, which often involved an economic interest and larger-sized groups (Haas 1973).

When considering politicians' reactions to weather modification, it is perhaps not surprising that state and federal legislators (and their constituents) tended to be in favor of federally financed weather modification efforts. Federal and state funding for such projects brought in income (e.g., through job creation and project-related spending) and created secondary economic benefits, such as money spent by project workers on food and fuel. Also, at least superficially, such efforts were often seen as alleviating a problem (e.g., a drought) that politicians could point to as a ''solution'' they provided for voters (Haas 1973).

Many of the U.S. state weather modification efforts between 1947 and 1980 were based on hope and supported by local political leaders using taxpayers' funds; damages from such efforts went largely uncharted (Taubenfeld 1967; Davis 1974) because of the difficulty of linking effect to cause. When considering possible compensation, not only did Haas (1973) find that many believed no compensation for uninsured losses should be provided, but those surveyed also did not suggest that the benefactors of weather modification should have to pay for weather modification services. The level of discussion and anxiety related to compensation of those harmed by either weather modification or SRM, combined with the other ethical issues, make this finding surprising (Samuels 1973; Weiss 1975, 1977; Shepherd et al. 2009; Suarez 2010; SRMGI 2011).

Unlike the generally positive views of local weather modification projects, views on hurricane modification were quite different. As SRM would be expected to do, hurricane efforts were designed to affect broad areas and, potentially, large human populations. In combination with not being able to prove or disprove whether particular tropical cyclones were natural or human induced, the public had very limited understanding of issues relating to the occurrence of and responsibility for unintended consequences (Kellogg and Schneider 1974; Weiss 1975; Weiss 1977). For these reasons, hurricane modification was a political and public hot potato that decision makers, federal agencies, and scientists preferred to avoid (Travis 2010).

Based on the experience with hurricane modification, the public is unlikely to be ambivalent about SRM efforts, which potentially have longer-term and certainly broader impacts and intentions. Elected leaders guiding these efforts are likely to be faced with political, social, or economic demands and agendas to some degree; factoring such concerns into decisions is, however, the nature of their jobs. If geoengineering choices or agendas end up being influenced by personal interest or if one group is favored over another (e.g., the wealthy or powerful favored over the poor), geoengineering decisions may lose credibility and legitimacy (Victor et al. 2009). Transparency and public input, as well as consideration of issues related to power and equity, will likely be necessary components of any SRM research and governance process (Rayner et al. 2009; Joronen et al. 2011; SRMGI 2011; Task Force on Climate Remediation Research 2011).

3. Elements of the U.S. federal weather modification governance structure

The structure of weather modification governance encompasses more than just the eight public laws generated during the period of study (see Table 3). Structural components also included participants (e.g., authorities making and implementing rules, scientists, the public); the facts, values, and actions that informed decision making and implementation; and links between weather modification actions and outcomes that influenced subsequent governance choices. An overview of these governance components is provided below and in Table 1.

a. *Governance authority*

U.S. federal weather modification suffered from a lack of leadership. While the White House and Congress occasionally—and, during these periods, passionately—paid attention to weather modification, such attention occurred in reaction to concerns about the Cold War, the advance of communism, the validity of weather modification claims and expenditures, the economic and environmental benefits that might accrue to constituents, and concern about the military's hostile use of the technology. Even though competition with the Soviet Union and worries about communism's spread had the most staying power, focus on weather modification as an aid to address these interests waxed and waned. The White House or Congress might have deputized a single agency with the authority to manage a federal weather modification program; Lambright and Changnon (1989) proposed that doing so might have sustained federal weather modification programs beyond 1980. While this authority was formally given to NSF for 10 yr, the informal reality was that each agency receiving funding for weather modification acted largely independently, generally based on congressional committee mandates.

Charged with developing a national weather modification policy in 1976 (Public Law 94-490), the Department of Commerce (DoC) recognized the need for better leadership and coordination of federal research. The resulting DoC policy report suggested that coordination occur under the Committee on Atmosphere and Oceans of the Federal Coordinating Council for Science, Engineering, and Technology, which provided advice to the White House Office of Science and Technology Policy's (OSTP) director (U.S. Department of Commerce 1979).[1] Similarly, for SRM the Task Force on Climate Remediation Research (2011, p. 17) addressed leadership issues, calling for White House coordination of any U.S. climate remediation program through OSTP, in cooperation with other executive branch departments and agencies.

[1] Reagan administration funding cuts to the federal weather modification program meant that this policy recommendation was not pursued.

The nature of federal budgeting and oversight and agency interactions make solving this issue of leadership a difficult one. Anointing a lead agency with authority or creating an effective interagency program is complicated by the reality that limited flexibility exists for the executive branch, Congress, and the agencies themselves to shift oversight responsibilities or funding even when all agree that doing so best serves the public need. The U.S. Global Climate Change Research Program (USGCRP), which coordinates U.S. agency and department efforts to carry out research on global change, offers a modern example of the difficulties of leading an interagency research program. In reviewing the updated USGCRP strategic plan, the NRC (2011) identified shortcomings that could adversely affect achieving desired research functions. Among these were a lack of expertise or within-agency mandate to pursue critical research and the lack of a governance structure empowered to implement decisions and allocate funding, both characteristics deemed as lacking in the federal weather modification program. Without focused support from the U.S. executive or legislative branches, USGCRP—or SRM—research efforts may face similar obstacles to those faced by the U.S. weather modification program.

b. *Institutions and communities involved in federal weather modification programs*

A variety of institutions contributed to developing U.S. weather modification governance. Avenues of participation included creation of policies, supplying funding or expertise to expand understanding of weather modification science and technology, running research and operational programs, and analysis of weather modification outcomes. Of the institutions involved, Congress and the White House had the greatest influence but, as described above, attention from these sources was fragmented with focus occurring largely as a result of crises and/or perceived public need. Federal organizations—NSF; ICAS; and the Departments of Commerce, Interior, and Defense—established weather modification rules through both formal policies (e.g., annual DoC reporting) and informal rules created by organizations working largely independent of a central authority (Weather Modification Advisory Board 1978; U.S. Department of Commerce 1979).

Another set of institutions that might have contributed more to the governance process were the courts: local, state, and federal. However, in order to file a legal suit, a plaintiff must be able to demonstrate proof of harm, which, lacking experimental confirmation of the efficacy of weather modification, proved difficult; similarly, proving SRM harm (or benefit) is likely to be challenging. Details on the lack of litigation and the potential for future litigation to advance the governance structure, transparency of research, and public information are provided below. Like the courts, the U.S. public played a bystander role in weather modification research and governance development; this is unlikely to be the case for SRM. Ironically, in the case of local-scale weather modification, the public might have supported sustaining a national weather modification program, with evidence generally showing a backing of or ambivalence toward weather modification use (Haas 1973: Changnon et al. 1978). However, federal efforts to inform the public about weather modification rarely occurred.

c. *Rules: National and international policies*

During the period 1947–80, federal legislation largely revolved around research-program authorization and direction, collection and reporting of weather modification activities, and commissioning of major studies regarding recommended federal policy and the status of weather modification technology (CRS 2004). Of all of the public laws passed, only two (which are related) remain in play today. Public Law 92-205 tasked the DoC with monitoring U.S. weather modification efforts, making reporting of weather modification programs to a federal authority a requirement (this law will likely apply to geoengineering efforts, which result in weather modification on time scales of sufficient duration to affect the climate). However, as was the case with NSF, beyond being a reporting repository, DoC's authority over weather modification efforts was minimal.

In terms of international policy, a 1975 agreement between the United States and Canada laid out terms related to notification and exchange of information and consultation regarding weather modification projects conducted near the U.S.–Canadian border (Canadian Department of Foreign Affairs and International Trade 1975). With only one other agreement (between Yugoslavia and Bulgaria in 1973; Weiss 1977) found in a review of the literature, it seems clear that there were few incentives for nations to establish cooperative research or deployment measures. A step in this direction occurred with the development of the United Nations Environment Programme's (UNEP) provisions for cooperation between states in weather modification (UNEP 1980). Created in cooperation with the World Meteorological Organization (WMO), the UNEP guidelines advocated for cooperation between nations pursuing weather modification to ensure that such efforts did not inflict damage on areas outside of national boundaries (Bodansky 1996); however, guideline promulgation did not go beyond the level of a UNEP Governing Council decision (Sand 1991).

For weather modification, some (e.g., Samuels 1973; Weiss 1975) suggested an organization like the WMO might have provided the required impetus for developing global weather modification governance because of its history of facilitating exchange of meteorological data and expertise, and because such an organization did not have an allegiance to a given nation's political agenda. While the influence of a WMO-like organization on governance framing and decisions for geoengineering may occur, the level of influence is likely to vary based on situational—that is, political, environmental, social, or economic—context. Clark et al. (2006) point out that such influence may best come when cognitive or normative uncertainty create ''fluid moments in history'' with ''openings for rethinking'' in which decision makers seek out new information.

While such an opportunity did not occur in the case of weather modification, it did in relation to scientists' warnings about the adverse environmental effects of nuclear weapons detonation and the effects of a nuclear war on ozone and temperature in the 1980s (Pittock et al. 1986). The research, combined with a number of ''rethinking'' opportunities (e.g., struggling national economies, high military budgets, threat of space-weapon buildup with the U.S. Strategic Defense Initiative, and changing national politics) contributed to the United States and Soviet Union signing the 1987 Intermediate-Range Nuclear Forces Treaty. The issue of climate change may generate the same level of political action at some point.

On both the domestic and international fronts, litigation might have been an important driver of governance as it reflects contemporary values and concerns of public and private interests and, lacking robust federal regulations, weather modification governance gaps might have been covered through legal action. In addition to military classification of experiments, which effectively eliminated civilian litigation (Ball 1949), few court cases related to weather modification arose during the period considered because of the difficulty—if not impossibility—of incontrovertibly attributing a particular loss to a given weather modification operation (Ball 1949; Davis 1974). In a rare example where a plaintiff successfully argued a tort case against a cloud seeding company, Davis (1974) recounts that the judge involved issued a temporary restraining order on behalf of ranchers against a company providing hail-suppression services, relying on ranchers' eyewitness testimony on cloud dissipation. While an appeals court did not overrule this testimony, the lack of subsequent cases relying on the ruling suggests inherent weaknesses in the decision.

d. Values: Underlying motivations driving weather modification use

Values such as power, wealth, respect, well-being, rectitude, skill, enlightenment, and affection (Lasswell 1958) were likely the most important drivers behind many of the U.S. weather modification governance decisions made between 1947 and 1980. Values related to global, national, and personal power (e.g., U.S. dominance on the global stage), wealth, and security (e.g., economic and political), as well as enlightenment and skills offered by the pursuit of weather modification and the related study and understanding of the atmosphere, are included to at least some degree in the governance components outlined above. Other less obvious values include rectitude, respect, and affection, as demonstrated, for example, by politicians' actions in an effort to show voters their sensitivity to local needs or by scientists motivated by doing research to aid society. Had they been explicitly considered, assessing these values in relation to actions might have helped scientists, decision makers, and funding and governing organizations avoid some of the reactive governance choices made during the heydays of weather modification research.

4. A critique of U.S. weather modification governance

U.S. federal weather modification programs for the time period considered would likely have benefitted from more effective, less reactive policies, better leadership, and clarification of goals and values. In considering U.S. federal weather modification governance, decision makers might have staved off ad hoc creation of policies by establishing desired goals at the outset of the process. With clearer objectives in mind, federal leaders desiring an application-focused program might have given a mission-oriented agency (e.g., NOAA or DoI/Bureau of Reclamation) the responsibility for advancing understanding of the effects of cloud seeding from the outset. By endowing this lead agency with authority and stable funding—thereby heightening agency leaders' interest in maintaining a research program—federal-level research might have been sustained and a better scientific and probabilistic understanding about weather modification's effects might have been gained. Alternatively, a goal-oriented Congress might have had a greater appreciation of the value of experimental weather modification and NSF's leadership role might have endured, leading to research that advanced understanding of weather modification's effects.

Generation of friendly competition between public and private research entities might also have maintained federal interest and established efficacy of weather modification techniques; this has been a successful approach for advancing emerging technologies such as computing, telecommunications, nuclear technology, and nanotechnology. While private sector interests became—and still are—involved in local weather modification efforts, they generally did not run projects with intent to prove or disprove efficacy of weather modification techniques. Moreover, many of the leading research organizations did not pursue weather modification research, likely because of concern about legal repercussions resulting from possible environmental harm; GE certainly had such reservations.

Collingridge (1980) suggested that decision and governance-development processes for new and emerging technologies work best when designed to maximize flexibility and reversibility and minimize losses; in contrast, federal weather modification governance and decision processes were not generally designed with flexibility or reversibility in mind. One means of increasing flexibility might have been to support ongoing assessment and incorporate new insights into the existing weather modification governance; Brunner and Lynch (2010) considered such efforts to be critical to generating governance that can respond nimbly to change in societal and environmental context, knowledge, values, goals, etc. Ideally, part of an evaluation process would have been consideration of both those benefitting from weather modification and those adversely affected (for geoengineering, such efforts will be critical). Such approaches, however, require proactive rather than reactive policy creation as often as is realistically possible.

The courts might have played a greater role in weather modification governance, but setting of legal precedent was stymied by classification of weather modification as a military secret and a lack of experimental data to prove or disprove weather modification efficacy. While not expected to be the leading contributor to advancing the governance process, courts interpret and enforce rules, regulations, contracts, and duties of care, creating due process procedures and real-life applications of governance policies and boundaries. Litigation, which involves fact finding and explanations of actions and intent, might have led to greater research transparency and would have provided a forum to ensure equity for those believing themselves adversely affected by weather modification.

In sum, the U.S. federal weather modification program would likely have benefitted from committed agency support (ideally the agency would have had both authority and some dedicated funding), healthy public–private research competition with a focus on results validation, proactive decision making that incorporated assessment and learning into the governance process, and a greater degree of transparency and public involvement. Each of these may be important to consider in assessing and formulating the range of values, rules, and institutions that will necessarily become associated with SRM governance, whether through a preplanned process or evolving through uncoordinated experiences, in the event that such work goes forward.

a. North Dakota: Considering an enduring weather modification program

Similar to the federal situation, weather modification efforts have occurred in North Dakota since the 1950s, funded by ranchers and farmers to reduce hail damage (North Dakota experiences some of the highest levels of hail damage to agricultural crops in the nation). In 1975, influenced by the grassroots efforts and study results from several universities in North and South Dakota that suggested cloud seeding might have positive influences on hail suppression (Butchbaker 1973; Atlas 1977), an official state weather modification program began. With a mission to regulate weather modification activities, share program costs, and support research focused on advancing weather modification science and technology, the original Weather Modification Board evolved into the Atmospheric Resource Board (ARB) in 1987. The ARB runs as a quasi-independent division of the State Water Commission, with a defined level of judicial, legislative, advisory, budgetary, and rulemaking authority and responsibility. ARB membership includes the director of the state aeronautics commission, a representative of the environmental section of the state department of health, the state engineer, and board members from each of the state's seven regional districts.

The ARB has a level of autonomy in running the statewide weather modification program. It has a dedicated budget and well-defined roles and responsibilities for the ARB, district, and county-level weather modification authorities, as spelled out in the North Dakota Century Code (the state's catalog of laws). In addition to the authority granted to the ARB members and executive director, who lead the state's weather modification program, influence exists in the hands of county weather modification authorities, which have the power to extend or suspend county participation. Tax revenues from counties participating in the state weather modification program fund two-thirds of total costs; use of county taxes is inherently more transparent than is the case at the federal level and likely results in county and state residents having greater awareness of program plans and outcomes. The public seems largely accepting of the state's weather modification efforts, but individuals have the opportunity to provide input via county review board and electoral processes, as well as through direct access to elected and appointed officials in counties participating in weather modification projects, and residents of nonparticipating counties have an indirect voice in program choices through their ARB representatives. With clear program goals—hail mitigation and precipitation enhancement during the agricultural growing season—ARB planning and assessment is proactive and responsive to public and regional desires, with plans made in consultation with district and county officials in advance of annual weather modification projects moving forward. Separate from the state's operational efforts, the ARB also runs research and development programs designed to assess the efficacy of weather modification techniques and technology (D. Langerud, ARB, 2012, personal communication). While smaller in scale from a management and operational perspective than the federal weather modification program, the longevity of North Dakota's program suggests that some aspects of its governance structure may be contributing to its success.

5. Conclusions: Lessons learned from the U.S. example

Many agree that SRM governance mechanisms must be developed in advance of research or deployment to assess SRM risks and benefits; regulate activities as required; and adjudicate issues related to transboundary effects and equity, among other concerns (Joronen et al. 2011; SRMGI 2011; Task Force on Climate Remediation Research 2011). While no governance framework currently exists that is capable of addressing the full range of possible outcomes that could result from SRM research or deployment, the conduct of the U.S. federal weather modification program seems to support the notion that SRM research would benefit if a considered governance structure were to be developed in advance of field-based research or deployment. Of note, the U.S. weather modification governance structure related only to field experiments, not to theoretical or laboratory-based studies. Should this governance precedent be used in thinking about geoengineering governance, taking a similar approach with regard to ''indoor'' research (e.g., modeling) may address concern (Caldeira 2011) about bureaucratization of such efforts while also affording public scrutiny of field-based efforts.

The preceding description of the U.S. federal weather modification program's governance structure largely offers ideas on what to avoid when designing a serviceable geoengineering governance framework. A federal weather modification program proved impossible to sustain; in contrast, state-run weather modification projects that were begun at roughly the same time as federal programs continue in many states. It seems likely that some of the unique characteristics of the governance structure may contribute to state-program longevity. As an example of success, North Dakota's weather modification program has explicit goals, empowered leadership, assessments that feed into future program choices, and bottom-up/top-down interactions that build in public input and transparency. Each of these may be a beneficial component of an SRM governance structure.

Given the complexities that a potential SRM governance framework will have to manage, the federal (and state) weather modification case is comparatively straightforward. However, it offers a starting point for considering geoengineering governance requirements if research and testing goes forward and suggests that value exists in putting in place a focused, systematic research program to avoid some of the federal weather modification program's missteps.

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