CRITICAL ISSUES IN WEATHER MODIFICATION

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Good afternoon Chairmen Hutchison and DeMint, Ranking Members Bill Nelson and Ben Nelson, and members of the Subcommittees. My name is Michael Garstang, and I am a Distinguished Emeritus Research Professor in the Department of Environmental Sciences at the University of Virginia. I'm a fellow of the American Meteorological Society (AMS) and have served on numerous AMS committees. I was also the chair of the 2003 National Research Council's (NRC) Committee on Critical Issues in Weather Modification Research. The National Research Council is the operating arm of the National Academies, chartered by Congress in 1863 to advise the government on matters of science and technology.

This afternoon I will give you a brief summary of the status of weather modification research, as described in our NRC report, the major uncertainties that exist, and convey the committee's conclusions and recommendations. We will also provide an Executive Summary of the report which lists the key findings and recommendations in greater detail.

Efforts to minimize harmful weather impacts go back far in time. In the last 30 years, significant evidence has accumulated that human activities unintentionally affect the weather on scales ranging from local to global. Many of the same fundamental principles underlie both intentional and unintentional weather modification. Yet during this 30-year time period, there has been a progressive decline in weather modification research. Research support related to weather modification in the United States had dropped to less than $0.5M per year in 1999 from a high of $20M in the late 1970s. During the same period, there have been significant advances in technology. This has greatly improved our ability to observe, understand, and predict the weather. These advances, however, have not been either collectively or persistently applied to the problem of weather modification.

This decline in research is likely the result of a combination of factors, including early overly-optimistic claims, unrealistic expectations, and failure to provide scientifically demonstrable successes. But despite these limitations, and because of considerable pressures resulting from drought, hail, floods, and storm damage, private and state agencies actually spend significant resources on attempts to modify the weather. In 2001, there were 66 operational weather modification programs in 10 states and much more activity overseas.

How do we overcome this disparity between our willingness to attempt to modify weather and our reluctance to fund research to understand such activities? The 2003 National Academies committee that I chaired was charged to provide an updated assessment of the current state and the future of weather modification research, from new technologies to advances in numerical modeling and operations. A summary of our report is included in my written testimony. In my comments, I want to focus on our conclusions and recommendations.

First, with a few exceptions, the committee concluded that there still is no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances encouraging results have been observed, but this evidence has not been subjected to adequate testing.

Second, despite this lack of proof, the committee concluded that scientific understanding has progressed on many fronts. For instance, there have been substantial improvements in the ice-nucleating capabilities of new seeding materials. Also, new technologies such as satellite imagery are giving us tools to better understand the microphysical processes that lead to precipitation, and these advances, in time can help focus and optimize weather modification research.

Third, the committee stated that if progress in establishing our capability to modify the weather is to be made, intellectual and technical resources must be brought to bear on the key uncertainties that hamper progress. For example, there are critical gaps in our understanding of the complex chain of physical processes that lead to rain, snow, and hail.

Finally, and most importantly, the committee called for the establishment of a coordinated national program of weather modification research designed to reduce these and other key uncertainties. The program should consist of a sustained research effort that uses a balanced approach of modeling, laboratory studies, and field measurements. Instead of focusing on near-term operational applications of weather modification, the program should address fundamental research questions. It should take full advantage of recent related research and advances in observational, computational, and statistical technologies, by:

- Capitalizing on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems;
- Improving model treatment of cloud and precipitation physics;
- Improving the use of current computational and data assimilation methods; and
- Capitalizing on existing field facilities and developing partnerships among research groups and select operational programs.

In the committee's opinion, it is premature to initiate large-scale operational weather modification programs. However, a great opportunity exists to coordinate research efforts to address the fundamental questions that will lead to credible scientific results. Focused investigation of atmospheric processes, coupled with technological applications, will advance understanding and bring many unexpected benefits and results. In time, this research will place us in a position to determine whether, how, and to what extent weather and weather systems can be modified.

CLOSING THOUGHTS

The NRC Committee emphasizes that weather modification should be viewed as a fundamental and legitimate element of atmospheric and environmental science. Owing to the growing demand for fresh water, the increasing levels of damage and loss of life resulting from severe weather, the undertaking of operational activities without the guidance of a careful scientific foundation, and the reality of inadvertent atmospheric changes, the scientific community now has the opportunity, challenge, and responsibility to assess the potential efficacy and value of intentional weather modification technologies.

Thank you for the opportunity to testify. I would be happy to answer any questions the Subcommittees might have.

EXECUTIVE SUMMARY

The weather on planet Earth is a vital and sometimes fatal force in human affairs. Efforts to control or reduce the harmful impacts of weather go back far in time. In recent decades our ability to observe and predict various types of meteorological systems has increased tremendously. Yet during this same period there has been a progressive decline in weather modification research. Extravagant claims, unrealistic expectations, and failure to provide scientifically demonstrable success are among the factors responsible for this decline. Significantly, every assessment of weather modification dating from the first National Academies' report in 1964 has found that scientific proof of the effectiveness of cloud seeding was lacking (with a few notable exceptions, such as the dispersion of cold fog). Each assessment also has called for a dedicated research effort directed at removing or reducing basic scientific uncertainties before proceeding with the application of weather modification methods. Yet, this type of intensive, committed effort has not been carried out.

In this, the latest National Academies' assessment of weather modification, the Committee was charged to provide an updated assessment of the ability of current and proposed weather modification capabilities to provide beneficial impacts on water resource management and weather hazard mitigation. It was asked to examine new technologies, such as ground-based, in situ, and satellite detection systems, and fast reacting seeding materials and dispensing methods. The Committee also was asked to review advances in numerical modeling on the cloud- and mesoscale and consider how improvements in computer capabilities might be applied to weather modification. This study was not designed to address policy implications of weather modification; rather it focused on the research and operational issues. Specifically, the Committee was asked to:

- review the current state of the sciences of weather modification and the role of weather prediction as it applies to weather modification, paying particular attention to the technological and methodological developments of the last decade;
- identify the critical uncertainties limiting advances in weather modification science and operation;
- identify future directions in weather modification research and operations for improving the management of water resources and the reduction in severe weather hazards; and
- suggest actions to identify the potential impacts of localized weather modification on large-scale weather and climate patterns.

ISSUES AND TRENDS IN WEATHER MODIFICATION

Motivation

Increasing demands for water make the potential for enhancing the sources, storage, and recycling of freshwater a legitimate area of study. Destruction and loss of life due to severe weather, which is increasing with population growth and changing demographics, require that we examine ways to reduce these impacts. In addition, there is ample evidence that human activities, such as the emission of industrial air pollution, can alter atmospheric processes on scales ranging from local precipitation patterns to global climate. These inadvertent impacts on weather and climate require a concerted research effort, yet the scientific community has largely failed to take advantage of the fact that many of the scientific underpinnings of intentional and unintentional weather modification are the same.

Current Operational and Research Efforts

Operational weather modification programs, which primarily involve cloud-seeding activities aimed at enhancing precipitation or mitigating hail fall, exist in more than 24 countries, and there were at least 66 operational programs being conducted in 10 states across the United States in 2001. No federal funding currently is supporting any of these operational activities in the United States. Despite the large number of operational activities, less than a handful of weather modification research programs are being conducted worldwide. After reaching a peak of $20 million per year in the late 1970s, support for weather modification research in the United States has dropped to less than $500,000 per year.

The Paradox

Clearly, there is a paradox in these divergent trends: The federal government is not willing to fund research to understand the efficacy of weather modification technologies, but others are willing to spend funds to apply these unproven techniques. Central to this paradox is the failure of past cloud-seeding experiments to provide an adequate verification of attempts at modifying the weather. A catch-22 ensues in which the inability to provide acceptable proof damages the credibility of the entire field, resulting in diminished scientific effort to address problems whose solutions would almost certainly lead to better evaluations.

Limitations and Problems

The dilemma in weather modification thus remains. We know that human activities can affect the weather, and we know that seeding will cause some changes to a cloud. However, we still are unable to translate these induced changes into verifiable changes in rainfall, hail fall, and snowfall on the ground, or to employ methods that produce credible, repeatable changes in precipitation. Among the factors that have contributed to an almost uniform failure to verify seeding effects are such uncertainties as the natural variability of precipitation, the inability to measure these variables with the required accuracy or resolution, the detection of a small induced effect under these conditions, and the need to randomize and replicate experiments.

CONCLUSIONS

The Committee concludes that there still is no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances there are strong indications of induced changes, but this evidence has not been subjected to tests of significance and reproducibility. This does not challenge the scientific basis of weather modification concepts. Rather it is the absence of adequate understanding of critical atmospheric processes that, in turn, lead to a failure in producing predictable, detectable, and verifiable results. Questions such as the transferability of seeding techniques or whether seeding in one location can reduce precipitation in other areas can only be addressed through sustained research of the underlying science combined with carefully crafted hypotheses and physical and statistical experiments.

Despite the lack of scientific proof, the Committee concludes that scientific understanding has progressed on many fronts since the last National Academies' report and that there have been many promising developments and advances. For instance, there have been substantial improvements in the ice-nucleating capabilities of new seeding materials. Recent experiments using hygroscopic seeding particles in water and ice (mixed-phase) clouds have shown encouraging results, with precipitation increases attributed to increasing the lifetime of the rain-producing systems. There are strong suggestions of positive seeding effects in winter orographic glaciogenic systems (i.e., cloud systems occurring over mountainous terrain). Satellite imagery has underlined the role of high concentrations of aerosols in influencing clouds, rain, and lightning, thus drawing the issues of intentional and inadvertent weather modification closer together. This and other recent work has highlighted critical questions about the microphysical processes leading to precipitation, the transport and dispersion of seeding material in the cloud volume, the effects of seeding on the dynamical growth of clouds, and the logistics of translating storm-scale effects into an area-wide precipitation effect. By isolating these critical questions, which currently hamper progress in weather modification, future research efforts can be focused and optimized.

Additional advances in observational, computational, and statistical technologies have been made over the past two to three decades that could be applied to weather modification. These include, respectively, the capabilities to (1) detect and quantify relevant variables on temporal and spatial scales not previously possible; (2) acquire, store, and process vast quantities of data; and (3) account for sources of uncertainty and incorporate complex spatial and temporal relationships. Computer power has enabled the development of models that range in scale from a single cloud to the global atmosphere. Numerical modeling simulations—validated by observations whenever possible—are useful for testing intentional weather modification and corresponding larger-scale effects. Few of these tools, however, have been applied in any collective and concerted fashion to resolve critical uncertainties in weather modification. These numerous methodological advances thus have not resulted in greater scientific understanding of the principles underlying weather modification. This has not been due to flawed science but to the lack of support for this particular field of the science over the past few decades. As a result there still is no conclusive scientific proof of the efficacy of intentional weather modification, although the probabilities for seeding-induced alterations are high in some instances. Despite this lack of scientific proof, operational weather modification programs to increase rain and snowfall and to suppress hail formation continue worldwide based on cost versus probabilistic benefit analyses.

RECOMMENDATIONS

Recommendation: Because weather modification could potentially contribute to alleviating water resource stresses and severe weather hazards, because weather modification is being attempted regardless of scientific proof supporting or refuting its efficacy, because inadvertent atmospheric changes are a reality, and because an entire suite of new tools and techniques now exist that could be applied to this issue, the Committee recommends that there be a renewed commitment to advancing our knowledge of fundamental atmospheric processes that are central to the issues of intentional and inadvertent weather modification. The lessons learned from such research are likely to have implications well beyond issues of weather modification. Sustainable use of atmospheric water resources and mitigation of the risks posed by hazardous weather are important goals that deserve to be addressed through a sustained research effort.

Recommendation: The Committee recommends that a coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding; it should be implemented using a balanced approach of modeling, laboratory studies, and field measurements designed to reduce the key uncertainties listed in Box ES.1. This program should not focus on near-term operational applications of weather modification; rather it should address fundamental research questions from these areas that currently impede progress and understanding of intentional and inadvertent weather modification. Because a comprehensive set of specific research questions cannot possibly be listed here, they should be defined by individual proposals funded by a national program. Nevertheless, examples of such questions may include the following:

- What is the background aerosol concentration in various places, at different times of the year, and during different meteorological conditions? To what extent would weather modification operations be dependent on these background concentrations?
- What is the variability of cloud and cell properties (including structure, intensity, evolution, and lifetime) within larger clusters, and how do clouds and cells interact with larger-scale systems? What are the effects of localized seeding on the larger systems in which the seeded clouds are embedded?
- How accurate are radar reflectivity measurements in measuring the differences between accumulated rainfall in seeded and unseeded clouds? How does seeding affect the drop-size distribution that determines the relationship between the measured radar parameter and actual rainfall at the surface?

BOX ES.1
Summary of Key Uncertainties
The statements in boldface type are considered to have the highest priority.

Cloud/precipitation microphysics issues

- **Background concentration, sizes, and chemical composition of aerosols that participate in cloud processes**
- Nucleation processes as they relate to chemical composition, sizes, and concentrations of hygroscopic aerosol particles
- Ice nucleation (primary and secondary)
- Evolution of the droplet spectra in clouds and processes that contribute to spectra broadening and the onset of coalescence
- Relative importance of drizzle in precipitation processes

Cloud dynamics issues

- **Cloud-to-cloud and mesoscale interactions as they relate to updraft and downdraft structures and cloud evolution and lifetimes**
- Cloud and sub-cloud dynamical interactions as they relate to precipitation amounts and the size spectrum of hydrometeors
- Microphysical, thermodynamical, and dynamical interactions within clouds

Cloud modeling issues

- **Combination of the best cloud models with advanced observing systems in carefully designed field tests and experiments**
- Extension of existing and development of new cloud-resolving models explicitly applied to weather modification
- Application of short-term predictive models including precipitation forecasts and data assimilation and adjoint methodology in treated and untreated situations
- Evaluation of predictive models for severe weather events and establishment of current predictive capabilities including probabilistic forecasts
- Advancement of the capabilities in cloud models to simulate dispersion trajectories of seeding material
- Use of cloud models to examine effects of cloud seeding outside of seeded areas
- Combination of cloud models with statistical analysis to establish seeding effects

Seeding-related issues

- **Targeting of seeding agents, diffusion and transport of seeding material, and spread of seeding effects throughout the cloud volume**
- **Measurement capabilities and limitations of cell-tracking software, radar, and technologies to observe seeding effects**
- Analysis of recent observations with new instruments of high concentrations of ice crystals
- Interactions between different hydrometeors in clouds and how to best model them
- Modeling and prediction of treated and untreated conditions for simulation
- Mechanisms of transferring the storm-scale effect into an area-wide precipitation effect and tracking possible downwind changes at the single cell, cloud cluster, and floating target scales

The tasks involved in weather modification research fall within the mission responsibilities of several government departments and agencies, and careful coordination of these tasks will be required.

Recommendation: The Committee recommends that this coordinated research program include:

- **Capitalizing on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems** (e.g., Doppler lidars and airborne radars, microwave radiometers, millimeter-wave and polarimetric cloud radars, global positioning system (GPS) and cell-tracking software, the Cloud Particle Imager, the Gerber Particle Volume Monitor, the Cloud Droplet Spectrometer). Initial field studies should concentrate on areas that are amenable to accurate numerical simulation and multiparameter, three-dimensional observations that allow the testing of clearly formulated physical hypotheses. Some especially promising possibilities where substantial further progress may occur (not listed in any priority) include

  - *Hygroscopic seeding to enhance rainfall.* The small-scale experiments and larger-scale coordinated field efforts proposed by the Mazatlan workshop on hygroscopic seeding (WMO, 2000) could form a starting point for such efforts. A randomized seeding program with concurrent physical measurements (conducted over a period as short as three years) could help scientists to either confirm or discard the statistical results of recent experiments.

➢ *Orographic cloud seeding to enhance precipitation.* Such a program could build on existing operational activities in the mountainous western United States. A randomized program that includes strong modeling and observational components, employing advanced computational and observational tools, could substantially enhance our understanding of seeding effects and winter orographic precipitation.

➢ *Studies of specific seeding effects.* This may include studies such as those of the initial droplet broadening and subsequent formation of drizzle and rain associated with hygroscopic seeding, or of the role of large (>1 μm) particles (e.g., sea spray) in reducing droplet concentrations in polluted regions where precipitation is suppressed due to excess concentrations of small cloud condensation nuclei (CCN).

- **Improving cloud model treatment of cloud and precipitation physics.** Special focus is needed on modeling CCN, ice nuclei processes, and the growth, collision, breakup, and coalescence of water drops and ice particles. Such studies must be based on cloud physics laboratory measurements, tested and tuned in model studies, and validated by in situ and ground observations.

- **Improving and using current computational and data assimilation capabilities.** Advances are needed to allow rapid processing of large quantities of data from new observations and better simulation of moist cloud and precipitation processes. These models could subsequently be used as planning and diagnostic tools in future weather modification studies, and to develop techniques to assist in the evaluation of seeding effects.

- **Capitalizing on existing field facilities and developing partnerships among research groups and select operational programs**. Research in weather modification should take full advantage of opportunities offered by other field research programs and by operational weather modification activities. Modest additional research efforts directed at the types of research questions mentioned above can be added with minimal interference to existing programs. A particularly promising opportunity for such a partnership is the Department of Energy Atmospheric Radiation Measurement program/Cloud and Radiation Test bed (DOE ARM/CART) site in the southern Great Plains (Oklahoma/Kansas) augmented by the National Aeronautics and Space Administration (NASA) Global Precipitation Mission. This site provides a concentration of the most advanced observing systems and an infrastructural base for sustained basic research. The National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory (NOAA/ETL) also could serve as important focal points for weather modification research.

In pursuing research related to weather modification explicit, financial and collegial support should be given to young aspiring scientists to enable them to contribute to our fundamental store of knowledge about methods to enhance atmospheric resources and reduce the impacts of hazardous weather. It must be acknowledged that issues related to weather modification go well beyond the limits of physical science. Such issues involve society as a whole, and scientific weather modification research should be accompanied by parallel social, political, economic, environmental, and legal studies.

The Committee emphasizes that weather modification should be viewed as a fundamental and legitimate element of atmospheric and environmental science. Owing to the growing demand for fresh water, the increasing levels of damage and loss of life resulting from severe weather, the undertaking of operational activities without the guidance of a careful scientific foundation, and the reality of inadvertent atmospheric changes, the scientific community now has the opportunity, challenge, and responsibility to assess the potential efficacy and value of intentional weather modification technologies.

Closing Thoughts

The Academy Committee emphasizes that weather modification should be viewed as a fundamental and legitimate element of atmospheric and environmental science. The growing demand for fresh water, the increasing levels of damage and loss of life resulting from severe weather, the undertaking of operational activities without the guidance of a careful scientific foundation, and the reality of inadvertent atmospheric changes gives the scientific community the opportunity, challenge, and the responsibility to determine how and to what extent humans can influence the weather.