United States Government Accountability Office

Report to Congressional Requesters

December 2024

TECHNOLOGY ASSESSMENT

Cloud Seeding Technology

Assessing Effectiveness and Other Challenges

GAO-25-107328

The cover image depicts a view of Lake Mead with a lower water level caused by drought, snow-covered mountains, and rain over a field of crops.

Cover source: John(Lake Mead)/Chris(snow-covered mountain)/New Africa(rain over field of crops)/Daria(clouds)/stock.adobe.com; GAO (composite). | GAO-25-107328

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Highlights of GAO-25-107328, a report to congressional requesters

December 2024

Why GAO did this study

According to the Fifth National Climate Assessment, demand for water is increasing and the frequency and intensity of drought are projected to worsen in the western U.S. The ability to increase precipitation through cloud seeding could help mitigate some of the water management challenges caused by drought. Cloud seeding has been practiced in the U.S. since the 1940s. Recently however, advances in radar and sensor technology have enabled research with enough precision to show that cloud seeding may be effective under certain conditions.

This report discusses (1) the emerging and current technologies for cloud seeding (and weather modification generally), (2) the potential benefits of cloud seeding, (3) challenges surrounding the use and development of cloud seeding, and (4) policy options that may help address challenges or enhance benefits of cloud seeding.

GAO reviewed cloud seeding technology across development and operational stages; interviewed a range of stakeholder groups, including government, industry, academia, and professional organizations; convened an expert meeting that included academics, state and federal agency officials, and representatives from industry organizations. We also reviewed key reports and scientific literature. GAO is identifying policy options in this report (see next page).

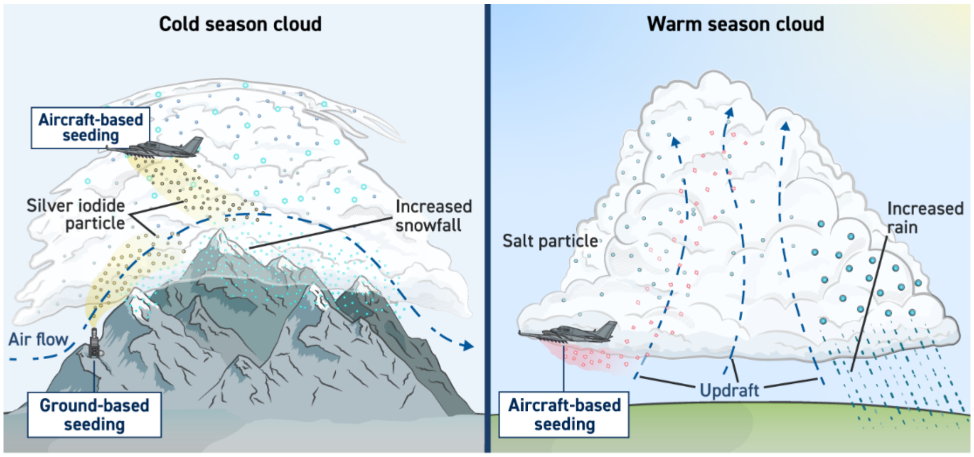
View GAO-25-107328. For more information, contact Karen L. Howard, PhD, at (202) 512-6888 or HowardK@gao.gov.

What GAO found

Cloud seeding is a decades-old approach to modifying weather that uses a range of supporting technologies for research and operations. According to NOAA, the most common uses of cloud seeding are to increase precipitation or suppress hail, usually by adding tiny particles of silver iodide. Nine U.S. states are currently using it, while ten have banned or have considered banning cloud seeding or weather modification in general. Federal cloud seeding involvement and support is minimal.

Cloud seeding may increase water availability and result in economic, environmental, and human health benefits. In the studies GAO reviewed, estimates of the additional precipitation ranged from 0 to 20 percent. However, it is difficult to evaluate the effects of cloud seeding due to limitations of effectiveness research.

Figure: Cold season and warm season cloud seeding



Sources: GAO summary of information from North Dakota Atmospheric Resources Board (http://www.nawmc.org/cloudseeding/methods.html) and *Can we control the weather?*, HOWSTUFFWORKS (https://science.howstuffworks.com/nature/control-weather.htm); GAO (illustration). | GAO-25-107328

GAO identified challenges to the use and development of cloud seeding, including:

- Reliable information is lacking on the conduct of optimal, effective cloud seeding and its benefits and effects. Without such information, operations will be less effective and the return on funding investments is unclear.
- Cloud seeding operations can only enhance precipitation when the right kind of clouds are present, which limits opportunities for success.
- Existing research we reviewed, while limited to a handful of recent studies, suggests silver iodide does not pose an environmental or health concern at current levels. However, it is not known whether more widespread use of silver iodide would have an effect on public health or the environment.
- Federal reporting requirements may not include all information necessary to adequately monitor cloud seeding. As a result, opportunities to better evaluate the benefits and potential effects of cloud seeding may be missed.
- The public may not fully understand cloud seeding, including how it differs from geoengineering, which affects the climate on longer time scales.

GAO identified five policy options that could help address these challenges or enhance potential benefits. These options are intended to inform policymakers of potential policy implementations. For the purposes of this report, 'policymakers' includes Congress, federal and state agencies, research institutions, industry, and other stakeholders. The status quo option illustrates a scenario in which current efforts proceed without intervention.

Policy Options to Help Address Challenges to the Use and Development of Cloud Seeding

Policy Option	Opportunities	Considerations
Maintain status quo efforts (report p. 21) *For example, cloud seeding operators, federal agencies, and researchers continue to apply technologies and approaches that are already tested and commercially available.*	• Some current state programs may already be optimized for local conditions. • Additional resources and time that may be required for other policy options could instead be used for other priorities.	• Current efforts are not likely to address all challenges described in this report.
Encourage targeted research to reduce uncertainty (report p. 22) *For example, government entities, researchers, and operators could promote and support research partnerships to address uncertainties.*	• Partnerships could enable more coordination and focus on local needs and broader issues, such as basic cloud-physics questions while improving local commercial operations. • More research could lead to better understanding of potential environmental and human health concerns of seeding. • More awareness of benefits could improve use of funds and awareness of equity issues.	• The public and policymakers often face short-term pressures regarding water, but cloud seeding research is best done over the long-term. • More research may not be enough to address some uncertainties. • New partnerships may also require more deliberate planning and consultation across sectors to identify suitable groups.
Support more evidence-based operations (report p. 22) *For example, policymakers could use licensing and permitting requirements to ensure operations conduct evaluations.*	• Ensuring evaluations are done consistently across cloud seeding operations could help address standardization challenges.	• Required funding and expertise for evaluations may not be available.
Improve monitoring and oversight (report p. 23) *For example, NOAA could use its existing authority to work with other government entities, researchers, and operators to update required data for reporting, and make changes to improve standardization of annual reports.*	• Better quality and transparency of information would improve broad understanding of cloud seeding. • NOAA's weather modification reporting form could require more specific information (e.g., flare constituents and seeding yield statistics). • Standardized federal data and reporting could improve data uniformity, making research and understanding generalizable and better support independent evaluations.	• Managing the increased volume and rate of data may become cost prohibitive. • Some operators may not share some information on cloud seeding flares due to proprietary concerns. • Various entities may lack incentives or awareness of reporting requirement. • Groups may also vary in their ability to report information due to funding and operational constraints.
Expand education and outreach (report p. 24) *For example, government entities, industry associations, scientific societies, researchers, and operators could promote awareness of the distinction between long-term climate or geoengineering applications and short-term cloud seeding to alter local precipitation.*	• Better understanding of definitions and differences can inform debate about potential risks and benefits of cloud seeding.	• Better understanding of definitions may not address some sources of negative public perception. • Additional funding would likely be required for larger outreach initiatives.

Source: GAO. | GAO-25-107328

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Abbreviations

ASCE	American Society of Civil Engineers
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
LIDAR	Light Detection and Ranging
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
TSCA	Toxic Substances Control Act
UAS	Uncrewed Aircraft Systems
USDA	U.S. Department of Agriculture
WMO	World Meteorological Organization

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December 19, 2024

The Honorable Frank D. Lucas
Chairman
Committee on Science, Space, and Technology
House of Representatives

The Honorable Bill Posey
House of Representatives

Extreme weather events have increased in frequency and intensity and may further increase because of climate change, according to the Fifth National Climate Assessment report.[1] For example, the assessment report notes drought is an ongoing issue across parts of the American West caused by natural climate variability and a warmer atmosphere. In addition, increased populations, aging infrastructure, and environmental requirements are increasing the strain on water and hydropower resources in the region. In 2022, Congress appropriated $4 billion to mitigate the effects of drought in the western U.S.[2] In 2023, damages from drought totaled over $14 billion, according to the National Oceanic and Atmospheric Administration (NOAA). In 2024, the U.S. Department of Agriculture (USDA) announced it will invest $400 million to help farmers continue production while also conserving water across the West.[3] Irrigation, which has enabled agriculture in previously inhospitable areas, is creating a deficit in some groundwater and reservoir reserves.

Cloud seeding, which seeks to modify local precipitation, may help mitigate some of these water management challenges. However, despite research and operations since the 1940s, it is only within the last few decades that advances in computer modeling and sensor technologies, such as radar, have enabled more detailed studies of cloud seeding and its effect on precipitation. GAO reports on cloud seeding issued in the 1970s preceded these advancements but noted that efforts to increase rainfall had been disappointing, critical scientific questions were unanswered, and research was uncoordinated.[4] Cloud seeding techniques are similar to those used for some types of climate engineering (or geoengineering), which generally seeks to alter the climate in ways that last longer and are less local. In 2011, GAO reported on climate engineering, finding

[1] U.S. Global Change Research Program, *Fifth National Climate Assessment*, (Washington, D.C.: Nov. 2023).

[2] Inflation Reduction Act of 2022, Pub. L. No. 117-169, § 50233, 136 Stat. 1818, 2053-54.

[3] U.S. Department of Agriculture, "Biden-Harris Administration Invests Up to $400 Million to Address Drought, Conserve Water through Production of Water-Saving Commodities," press release, August 1, 2024. https://www.usda.gov/media/press-releases/2024/08/01/biden-harris-administration-invests-400-million-address-drought.

[4] GAO, *Need for a National Weather Modification Research* Program, B-133202 (Washington, D.C.: Aug. 1974). GAO, *Federal Weather Modification Efforts Need Congressional Attention*, CED-80-5 (Washington, D.C.: Nov. 1979).

that public understanding of the topic was not well-developed and that many people were concerned about the potential harm of deploying technologies to alter the behavior of the Earth system.[5]

You asked us to conduct a technology assessment of weather modification technologies, including cloud seeding, and their potential effects and effectiveness for mitigating drought and other concerns. This report discusses (1) current and emerging technologies for cloud seeding—which is the primary form of weather modification—in the U.S. and other countries; (2) potential benefits of cloud seeding for the U.S.; (3) challenges that could hinder or result from the development and application of cloud seeding, including potential health and environmental effects; and (4) the extent to which policy options could help realize those benefits or address the challenges.

We interviewed agency officials and other stakeholders, including nonprofit organizations, industry associations, and academic researchers; visited research institutes and private companies involved in cloud seeding, including a manufacturer of technology used to support cloud seeding; held an expert meeting with participants representing different stakeholder groups; and reviewed agency documents and other literature. See appendix I for a full discussion of the objectives, scope, and methodology, appendix II for expert meeting participants, and appendix III for related GAO products.

We conducted our work from January 2024 through December 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[5]GAO, *Climate Engineering: Technical Status, Future Directions, and Potential Responses*, GAO-11-71 (Washington, D.C.: July 2011).

1 Background

1.1 What is cloud seeding?

Cloud seeding is a method of weather modification focused on producing short-term changes in precipitation. The Weather Modification Reporting Act of 1972 defines weather modification as "…any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere."[6] According to literature we reviewed, academic and private sector stakeholders we interviewed, and federal and state agencies we met with, the vast majority of weather modification activities occurring within the U.S. and abroad are cloud seeding. According to NOAA, the common reasons for seeding clouds are to enhance precipitation or suppress hail. Other activities intended to modify climate over longer time periods—such as solar radiation management, a type of geoengineering—may also be considered weather modification for the purposes of the Weather Modification Reporting Act but are beyond the scope of this report.[7] We will use the term "cloud seeding" or "seeding," unless specifically describing another method of weather modification.

The most frequently used cloud seeding approaches rely on the introduction of tiny particles (nuclei) into certain cloud types to trigger the formation of ice crystals (glaciogenic seeding) or rain droplets (hygroscopic seeding) from water already carried in the cloud that is not being efficiently turned into precipitation.[8] Clouds amenable to these methods include cold season clouds associated with mountainous terrain and warm season clouds associated with convective systems, including thunderstorms.

Such clouds are seeded to (1) increase snowfall from clouds overlying mountains (cold season orographic) by converting more supercooled liquid water to ice crystals,[9] and (2) increase rainfall from warm or mixed (i.e., cold and warm) clouds (warm season convective) by encouraging tiny cloud droplets to collide and coalesce, creating more raindrops that can reach the ground.[10] Thunderstorms are also seeded in an attempt to reduce hail severity. Figures 1 and 2 show the common types of cloud seeding.

[6]Weather Modification Reporting Act of 1972, Pub. L. No. 92-205, 85 Stat. 735 (1971) (codified, as amended, at 15 U.S.C. §§ 330-330e); 15 C.F.R. § 908.1; *see also* National Weather Modification Policy Act of 1976, Pub. L. No. 94-490, 90 Stat. 2359.

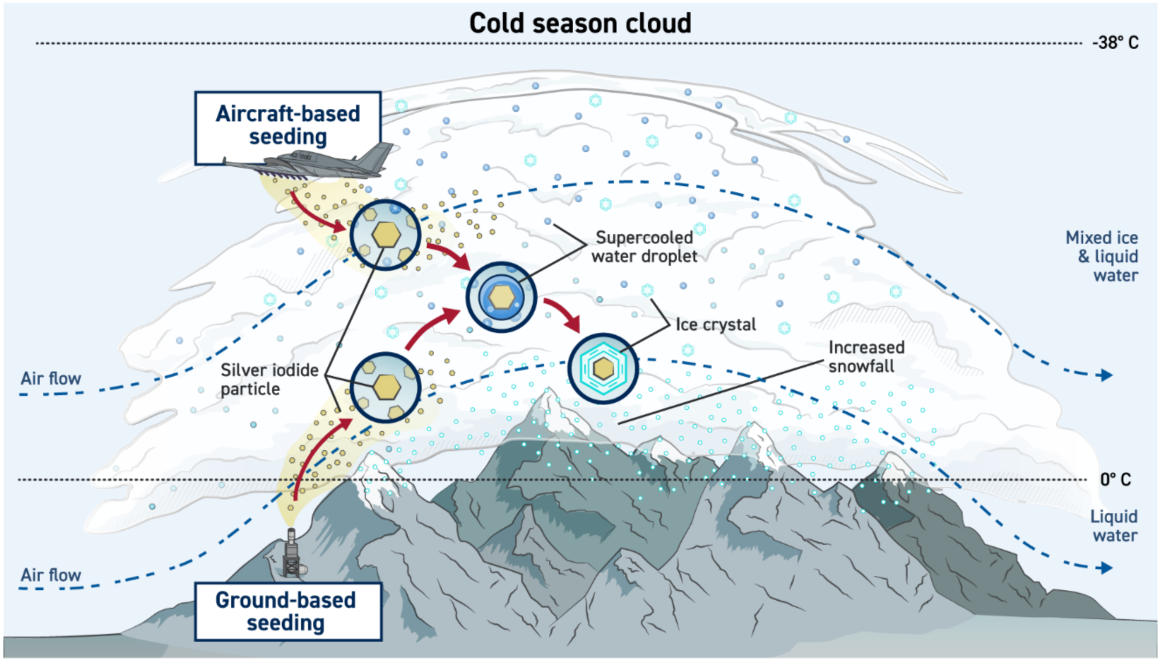
[7]National Oceanic and Atmospheric Administration (NOAA) officials and documents noted that activities intended to modify climate, including solar radiation management activities, should be reported under the agency's definition of weather modification. For more information on geoengineering, see GAO-11-71.

[8]Particles that are hygroscopic have a chemical affinity for water. Some warm season, mixed-phase seeding programs also use silver iodide and other forms of glaciogenic seeding. For example, North Dakota's cloud seeding program uses glaciogenic seeding in warm season clouds.

[9]Orographic clouds are created when air is lifted and forced to cool by terrain such as hills or mountains.

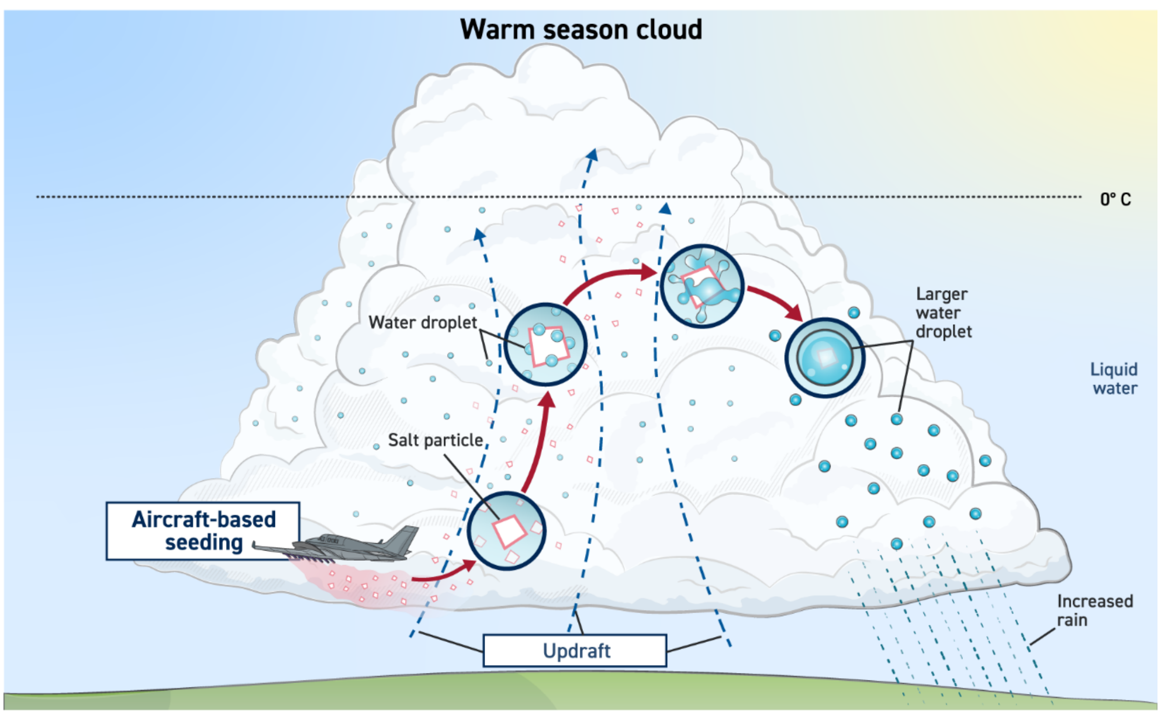
[10]Supercooled liquid water remains in liquid form below freezing temperature. When this water encounters very small nuclei or collides with objects, such as aircraft, it changes into ice.

Figure 1: Cold season cloud seeding over mountains



Sources: GAO summary of information from North Dakota Atmospheric Resources Board (http://www.nawmc.org/cloudseeding/methods.html) and Zamin A. Kanji, et al, *Overview of Ice Nucleating Particles* (https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0006.1); GAO (illustration). | GAO-25-107328

Figure 2: Warm season cloud seeding



Sources: GAO summary of information from North Dakota Atmospheric Resources Board (http://www.nawmc.org/cloudseeding/methods.html) and *Can we control the weather?*, HOWSTUFFWORKS (https://science.howstuffworks.com/nature/control-weather.htm); GAO (illustration). | GAO-25-107328

Scientists demonstrated the basis of cloud seeding in the 1940s, when they observed in the laboratory that water present in clouds could be artificially induced to create ice crystals using dry ice or silver iodide crystals (the latter is the most commonly used seeding agent in the U.S.). Extensive federal funding of research and development, including field experimentation, followed this discovery. For example, in fiscal year 1978, total federal funding for weather modification was approximately $68 million, in 2024 dollars.[11] During this period, researchers hypothesized chains of events (or "conceptual models") to describe conditions and processes needed for cloud seeding to work. But by the 1980s, inconclusive results led the federal government to cut funding. Nevertheless, non-federal cloud seeding operations and research have continued in parts of the U.S. and in other countries.

Over the past few decades, computer model and radar and sensor technology advances have improved evaluations of cloud processes and may help improve understanding of cloud seeding effects. For example, in 2017, a cold season field experiment directly observed the formation of ice crystals from supercooled liquid water following seeding and their fallout to the mountain surface—key documentation of the chain of events for this seeding approach.[12] A subsequent review of precipitation enhancement progress by the World Meteorological Organization (WMO) noted that the chain of events for cold season orographic cloud seeding is now reasonably well understood.

Other cloud seeding approaches remain emergent or in development. For example, the WMO review noted that substantial uncertainties remain to understand the chain of events when warm season clouds are seeded.[13] In addition, research to develop approaches to reduce lightning strikes or suppress hurricanes continues despite uncertain scientific plausibility. Australia and Japan are currently investigating the feasibility of tropical cyclone (e.g., typhoon or hurricane) suppression.[14] We did not identify any current U.S. research or operational programs for hurricane suppression.[15]

[11]GAO, CED-80-5.

[12]Jeffrey R. French et al., "Precipitation formation from orographic cloud seeding," *Proceedings of the National Academy of Sciences*, vol. 115 no. 6 (2018), https://doi.org/10.1073/pnas.1716995115.

[13]Andrea I. Flossmann et al., *Peer Review Report on Global Precipitation Enhancement Activities,* World Meteorological Organization, (2018) https://filecloud.wmo.int/share/s/_ujeyRLhRxGYsN05nO6X_Q.

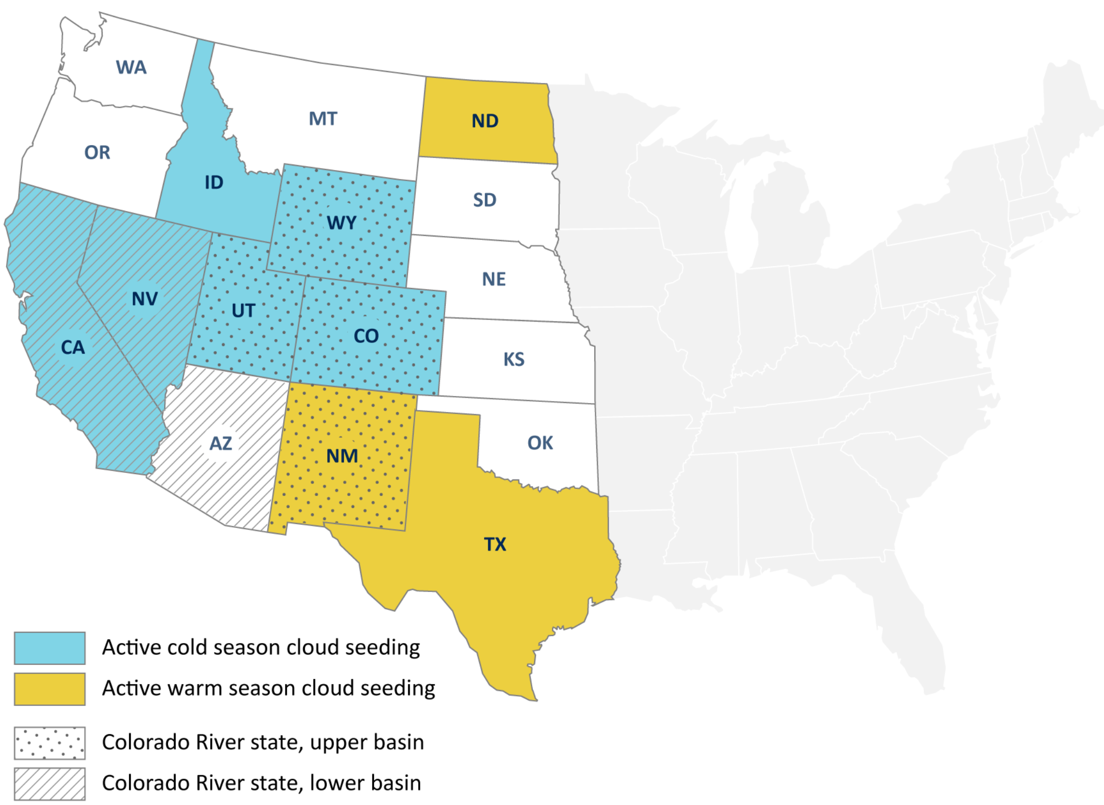
[14]Research efforts in Japan and Australia are focused on typhoons and cyclones, respectively, which are types of tropical cyclones like hurricanes. One researcher at Argonne National Laboratory told us she supports Australia's research program with her personal expertise in modeling hurricanes and aerosol cloud interactions, but this research is in an early phase conducted with models and they are still years from making field measurements of the effects of cloud seeding on hurricanes.

[15]The U.S. government conducted experiments starting in the 1940s with Project Cirrus and from the 1960s through 1980s with Project STORMFURY. Following the end of STORMFURY, the federal government has conducted no further experiments into hurricane suppression. Two reasons include: (1) the effects of intervention could not be distinguished from natural variability, and (2) observations of hurricanes indicated that seeding would be ineffective because there was too little supercooled liquid water available to seed and too much naturally occurring ice. For more information from NOAA on modifying hurricanes, see https://www.noaa.gov/news/fact-check-debunking-weather-modification-claims.

1.2 Cloud seeding in the U.S.

U.S. cloud seeding activities are primarily funded at the state level or below. As of July 2024, cloud seeding programs were active in at least nine states: California, Colorado, Idaho, Nevada, New Mexico, North Dakota, Texas, Utah, and Wyoming (see fig. 3). Among states identified that directly fund cloud seeding operations, Utah provides the most support. In 2023, Utah approved $12 million in one-time funding with an ongoing annual budget of $5 million. Other states identified typically provide a few million dollars or less annually. Arizona and New Mexico recently considered whether to support cloud seeding with state funds. Other state-level governments provide no direct support. For example, in California, state agencies do not directly fund cloud seeding, but may make grants to local agencies to enhance water supplies. The local agencies, which include utilities, water districts, and counties, can fund cloud seeding with a combination of grants and local revenue. In total, these agencies spend $5 million to $7 million annually on cloud seeding. Similarly, in Texas, cloud seeding projects are funded only by local sponsors at the water district or county level.

Figure 3: Map of states with active cloud seeding programs in 2024



Source: GAO summary of Weather Modification Association data (https://weathermod.org/project-locations/) and North American Weather Modification Council data (http://www.nawmc.org/); Map Resources (map outline). | GAO-25-107328

1.3 Cloud seeding in other countries

The extent and consistency of international support for cloud seeding varies. According to researchers and other stakeholders, interest in and funding for cloud seeding efforts often depend on immediate needs for water resources, and international programs may be suspended or cancelled when more abundant water returns. In 2015, the WMO reported that at least 50 countries had active weather modification programs.[16] According to an expert we interviewed, as of July 2024, the World Weather Research Programme Expert Team on Weather Modification has begun the process of updating its list of international programs. (See appendix IV for countries we identified as having cloud seeding programs active since 2020.)

According to our analysis of literature and interviews, several countries have extensive cloud seeding programs.[17] For example, China has the largest weather modification program (reportedly $2 billion dollars in total between 2014 and 2021, according to one research article).[18] In December 2020, the Chinese government announced plans to develop the capacity to modify weather over half its land territory by 2025.[19] According to a report from its National Center for Meteorology, Saudi Arabia spent over $256 million in 2022 to support the first year of its regional cloud seeding program.[20] The National Center of Meteorology United Arab Emirates Rain Enhancement Program funds cloud seeding research and operations (reportedly $22.5 million in grants since 2016, and unadjusted for inflation).[21] India funded a multi-year research program from 2009 to 2019 to examine the scientific basis for rain enhancement and has ongoing programs.[22] In 2019, two states in India reportedly approved $4.3 million and $6 million for cloud seeding to address drought.

1.4 Current and emerging cloud seeding technologies

Cloud seeding approaches rely on a set of technologies to deliver seeding particles to clouds suitable for seeding, at specific locations and times, to stimulate or enhance precipitation processes. Table 1 describes key categories of technologies that support cloud seeding. According to the WMO and

[16] World Meteorological Organization Documents on Weather Modification. Statement on Weather Modification, Phitsanulok, Thailand, March 17-19, 2015.

[17] We did not independently assess the accuracy of the spending amounts reported by these sources, or whether spending indicated the effectiveness of cloud seeding.

[18] Manon Simon et al., "Transboundary Implications of China's Weather Modification Programme," *Transnational Environmental Law*, vol. 12 no. 3 (2023), https://doi.org/10.1017/S2047102523000146.

[19] The State Council, The People's Republic of China, "China to forge ahead with weather modification service," press release, December 2, 2020, http://english.www.gov.cn/policies/latestreleases/202012/02/content_WS5fc76218c6d0f7257694125e.html.

[20] National Center for Meteorology Kingdom of Saudi Arabia, *Annual Report 2022 Regional Cloud Seeding Program, 1443-1444 A.H.* (2024).

[21] Youssef Wehbe et al., "Rethinking water security in a warming climate: rainfall enhancement as an innovative augmentation technique," *Climate and Atmospheric Science,* vol. 6 no. 171 (2023), https://doi.org/10.1038/s41612-023-00503-2. Alya Al Mazrouei, "UAE Rain Enhancement Program: A global nexus for a more resilient climate," presented at the ASEAN Regional Seminar on Weather Modification 2024, Chan Buri Province, Thailand, Oct. 19, 2024, https://awmc.royalrain.go.th/awmc2024/papers.html (accessed Dec. 6, 2024).

[22] Thara Prabhakaran et al., "CAIPEEX: Indian Cloud Seeding Scientific Experiment," *Bulletin of the American Meteorological Society*, vol. 104 no. 11 (2023), https://doi.org/10.1175/BAMS-D-21-0291.1.

stakeholders we interviewed, alternative technologies such as acoustic wave generators (e.g., "hail cannons"), electric field generators, and lasers have yet to be scientifically demonstrated and are therefore not included.[23]

Table 1: Examples of the categories of cloud seeding technologies

Category	Purpose	Technologies in regular use	Technologies in development or used infrequently
Seeding agent	Promote the formation of ice crystals or water droplets that grow and fall	Silver iodide, sodium chloride or other salts, dry ice, liquid propane	Organic matter from microbes, electrically charged water, engineered nanomaterials
Delivery mechanism	Disperse seeding particles into clouds	Pyrotechnic flares on aircraft, ground generators, artillery, rockets	Balloons, uncrewed aircraft systems (UAS)
Real-time sensors	Evaluate in-cloud conditions for seeding potential or effects of seeding activities afterwards	*Remote*: Doppler radar, LIDAR,[a] radiometers *In-situ*: liquid water probes, instruments to measure droplet or ice crystal sizes and shapes	*Remote*: phased array or portable radar, satellite-based sensors *In-situ*: miniaturized sensors for UAS, airborne mass spectrometers
Models and software	Plan seeding operations or assess effectiveness afterwards	Numerical weather forecast models, radar return analysis software	Cloud seeding models, and combined seeding and hydrology models
Observational infrastructure	Measure precipitation at the ground surface	Rain and snow gauges	Stream gauges, remote sampling by UAS
Experimental facilities	Examine properties of clouds and seeding agents under controlled conditions	Laboratory cloud chambers that replicate some natural conditions	Larger cloud chambers to simulate stronger updrafts and permit use of more advanced instrumentation

Source: GAO analysis of literature and interviews. | GAO-25-107328

[a]LIDAR, or light detection and ranging, is a remote sensing method that can measure aerosol particles, ice crystals, water vapor, and other constituents of the atmosphere using laser pulses.

1.5 Selected agency activities and relevant laws

Federal agencies have provided little direct support for cloud seeding activities or research since the early 2000s. However, in 2023 the Bureau of Reclamation provided a $2.4 million grant to the Southern Nevada Water Authority for cloud seeding operations in Colorado, Utah, and Wyoming intended to benefit the Colorado River and to better understand efficicacy of cloud seeding. Other agencies have provided some support for cloud seeding research in recent years. For example, the National Science Foundation (NSF) awarded nearly $3.5 million to a 2017 Idaho field experiment to observe and model

[23]Andrea I. Flossman et al., "Review of Advances in Precipitation Enhancement Research," *Bulletin of the American Meteorological Society*, vol. 100 no. 8 (2019), https://doi.org/10.1175/BAMS-D-18-0160.1.

cold season cloud seeding. USDA awarded $100,000 in 2021 to fund research examining seeding using electrostatically-charged water.

Agency officials told us that basic research into cloud physics and behavior and for other purposes may be useful for cloud seeding, and the Department of Energy, NOAA, and NSF fund such research. The Federal Aviation Administration (FAA) also funds research on supercooled liquid water, due to its role in aircraft icing. Agency officials told us this research is unlikely to benefit cloud seeding, but one researcher noted that icing and seeding take place in similar cloud conditions. Studies examining where supercooled liquid water occurs may therefore help improve cloud seeding operations by, for example, identifying favorable cloud conditions for seeding.

Few international or domestic regulations govern cloud seeding or other weather modification activities for peaceful purposes.[24] Instead, most cloud seeding and other weather modification governance has been formulated and enforced at the state level within the U.S. Two federal laws specifically address weather modification: the Weather Modification Reporting Act of 1972 and the National Weather Modification Policy Act of 1976.[25] The laws require that (1) NOAA maintain a record of U.S. weather modification activities; (2) operators report their activities; and (3) NOAA prepare a report on weather modification research; economic, legal, social, and ecological implications; and policy options, which it completed in 1979.[26]

In addition to these federal laws, at least 29 states and the District of Columbia have laws that address weather modification in some way, according to research published in 2021.[27] In 2024, Tennessee passed a law prohibiting cloud seeding and some other weather modification operations in the state.[28] Similar bills have been introduced in at least nine other state legislatures from January 2023 through mid-December 2024.[29]

State requirements for cloud seeding activities vary among the nine states we identified as having active cloud seeding programs (see table 2). For example, most of these state laws require operators to obtain a license or permit to conduct cloud seeding, but some states lack specific criteria to assess operator qualifications. States commonly require "suspension criteria"—rules to prevent flooding and other negative

[24]Military or hostile use of environmental modification (including cloud seeding or other weather modification) against another nation is prohibited under a United Nations convention ratified by the U.S. *See* Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, May 18, 1977, 31 U.S.T. 333, 1108 U.N.T.S. 151 (entered into force Oct. 5, 1978).

[25]Weather Modification Reporting Act of 1972, Pub. L. No. 92-205, 85 Stat. 735 (1971) (codified, as amended, at 15 U.S.C. §§ 330-330e); National Weather Modification Policy Act of 1976, Pub. L. No. 94-490, 90 Stat. 2359; *see also* 15 C.F.R. §§ 908.1-908.21.

[26]The report concluded that weather modification was scientifically possible and recommended that the federal government "…undertake a coherent research and development program." Department of Commerce, *National Weather Modification Policies and Program,* Submitted by the Secretary of Commerce in Compliance with Public Law 94-490. (Washington, D.C.: Nov. 1979)

[27]Manon Simon, "Enhancing the Weather: Governance of Weather Modification Activities of the United States," *William & Mary Environmental Law and Policy* Review, vol. 46, no. 1 (2021), https://scholarship.law.wm.edu/wmelpr/vol46/iss1/5.

[28]Tenn. Code. Ann. § 68-201-122 (2024).

[29]State legislators in Florida, Illinois, Kentucky, Minnesota, New Hampshire, Pennsylvania, Rhode Island, South Dakota, and Texas have introduced bills banning cloud seeding or other forms of weather modification.

outcomes by delineating when cloud seeding activities are prohibited. These rules may include limits based on the amount of water held in snowpack, or flood and other severe weather forecasts. All but one of the nine states have liability (i.e., financial responsibility) requirements specific to cloud seeding.

State requirements for the public disclosure of information about potential cloud seeding and reporting of completed activities may be limited or more comprehensive, with specific guidelines for content and timing. For example, Colorado requires applicants to publish a legal notice of intent, hold a public hearing and, once approved, notify stakeholders in a target area, including the county emergency manager and local National Weather Service office. Operators must provide reports annually that describe completed seeding activities and their estimated effectiveness. The state also requires periodic evaluation of the program using data and evaluation methods that differ from annual assessments. In contrast, Idaho laws do not require public notification of potential cloud seeding projects or an assessment of seeding effectiveness in its required annual reporting.

Table 2: Weather modification requirements identified in states with active cloud seeding programs

State	State reporting[a]	State approval[b]	Public participation[c]	Liability[d]
California	Yes	Yes[e]	Yes	No
Colorado	Yes	Yes	Yes	Yes
Idaho	Yes	Yes	No[f]	Yes
Nevada	Yes	Yes	Yes	Yes
New Mexico	Yes	Yes	Yes	Yes
North Dakota	Yes	Yes	Yes	Yes
Texas	Yes	Yes	Yes	Yes
Utah	Yes	Yes	Yes	Yes
Wyoming	Yes	Yes	No	Yes

Source: GAO analysis of active state weather modification programs, laws, and regulations. | GAO-25-107328

Note: Selection of states with active programs may be incomplete as we did not survey all 50 states to assess whether cloud seeding activities take place.

[a]State reporting refers to requirements for periodic reporting of cloud seeding activities to the state.

[b]State approval refers to requirements operators must meet, such as demonstrated competence, before they may conduct cloud seeding activities. Approval to conduct a specific cloud seeding project is also contingent on meeting certain requirements. Some states require separate approvals for operators and projects while others use a single process. States may exempt some sponsors or activities such as emergency response or research and development.

[c]Public participation refers to requirements that the public is notified of or participates in the approval process for a cloud seeding project (e.g., by public notice or hearings).

[d]Liability refers to a requirement for the operator to demonstrate financial responsibility for potential liabilities resulting from the operation. The degree of potential liability and what operators must provide to demonstrate financial responsibility varies between states. Some states or state funded programs may be immune from liability.

[e]California has additional requirements when seeding is targeted at protected state or federal lands.

[f]Idaho water users may petition the state to initiate cloud seeding.

2 Cloud Seeding May Have Benefits, but Estimating Effectiveness Is Challenging

We identified multiple benefits that may result from cloud seeding, including increased water supplies for agricultural and industrial purposes. However, we found that estimates of cloud seeding effectiveness vary and identified limitations to evaluating effectiveness, including the difficulty in estimating how much precipitation would have fallen without seeding.

2.1 Effective cloud seeding may result in multiple benefits

If successfully deployed, cloud seeding may have benefits in the following areas (see fig. 4):

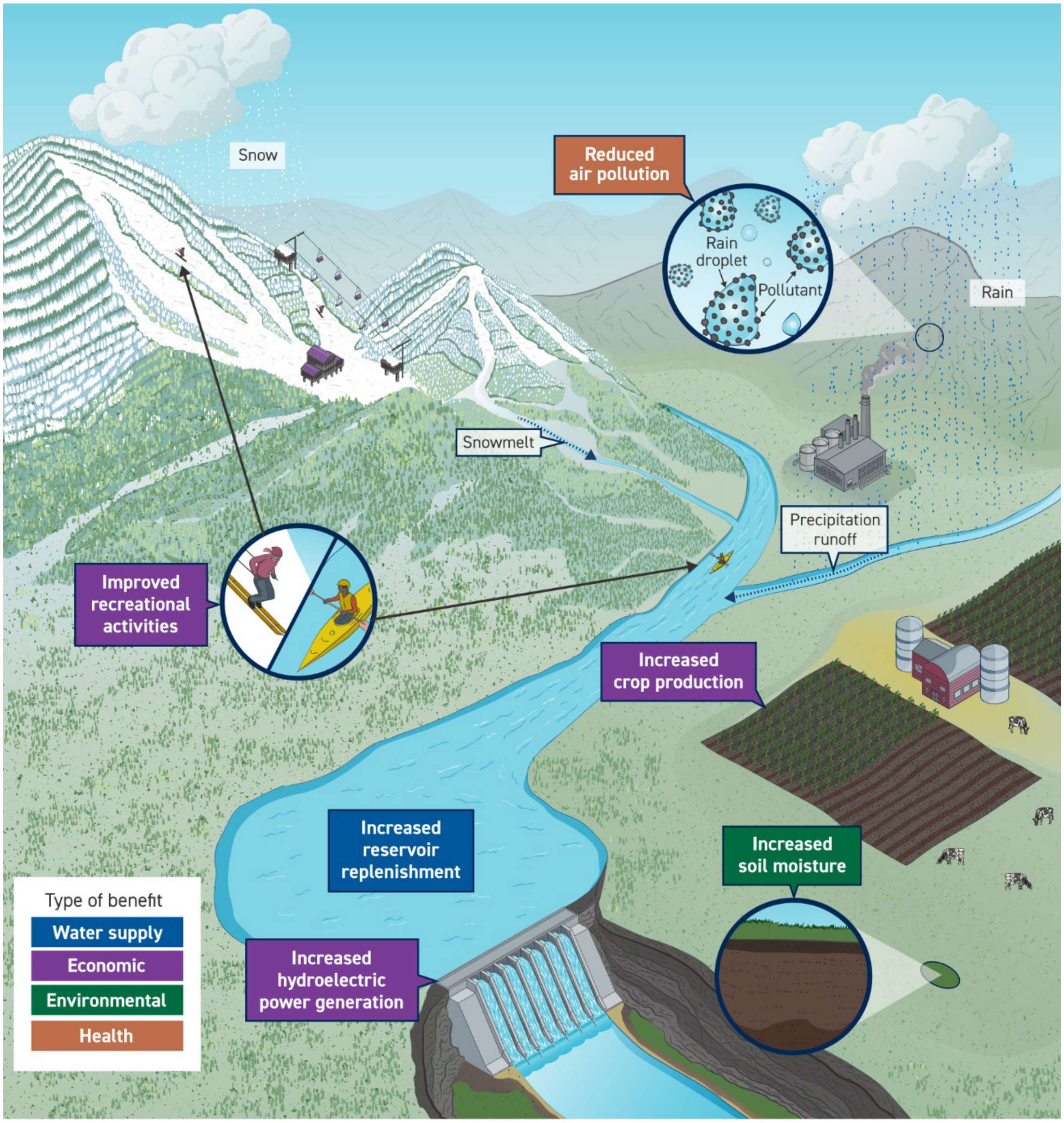
Water supply. Cloud seeding may increase total precipitation, thereby increasing water supply for agricultural, industrial, recreational, and municipal purposes by helping to replenish reservoirs and aquifers, among other uses. For example, one energy company told us they use cloud seeding to increase electricity production from hydroelectric dams, while ski resorts have used it with the goal of increasing snow.

Environmental. Increased precipitation can benefit plants, wildlife, and soil moisture levels, as well as reduce or prevent erosion. For example, it can mitigate drought-related threats to fish and may also reduce wildfire risk by increasing soil moisture and decreasing dry vegetation. Saudi Arabia has plans to use cloud seeding to establish new forests.

Health. Increased precipitation could reduce air pollution and its health effects. For example, China has reportedly used cloud seeding to reduce air pollution ahead of major events. India has reportedly considered using cloud seeding to reduce air pollution in New Delhi. In addition, Indonesia has reportedly used cloud seeding to mitigate forest fires, which may reduce air pollution.

Economic. The types of benefits listed above would result in economic benefits. For example, increased precipitation can reduce the need for additional water imports or drastic conservation measures. It can also increase crop production and revenue for agriculture and other industries. Hail suppression may reduce damage to agricultural products and property, and fog reduction may improve transportation safety. If feasible, hurricane suppression could reduce millions of dollars in damage and loss of life. Mitigating drought-related threats to plants and wildlife and improving human health could also result in substantial economic benefits.

Figure 4: Selected potential benefits of cloud seeding



Source: GAO (analysis and illustration). | GAO-25-107328

2.2 Estimates of effects and limitations to evaluating cloud seeding

Cloud seeding operators and researchers have attempted to evaluate the effects of cloud seeding. For example, they have estimated the additional precipitation generated and, in some cases, assessed its cost effectiveness. However, we found that the resulting estimates of additional precipitation can be imprecise and vary widely, which limits the ability to assess cost effectiveness and social benefits. For example, the WMO reports that the conceptual model for cold season cloud seeding is reasonably well understood, but that estimates of possible precipitation increases range widely, from 0 to 20 percent, for reasons that are unclear.[30] In contrast, for warm season cloud seeding, the WMO reports that substantial uncertainties in the conceptual model remain and does not provide a range of estimated precipitation increases.[31] Some studies in the U.S. do report estimated precipitation increases for warm season cloud seeding, but they lack key information about the statistical validity of their results. Evaluating cost effectiveness—such as by estimating the cost per acre-foot of water generated—relies on estimates of the amount of additional precipitation generated.[32] As a result, the uncertainty associated with these estimates of additional precipitation generated limits the ability of operators and researchers to evaluate cost effectiveness.

In addition, the specific metrics used can also introduce estimation difficulties and make interpretation more difficult. For example, reporting effects as a percent increase would inflate results when expected precipitation before cloud seeding is low, compared to when expected precipitation is higher.[33] As a result, policymakers may have challenges interpreting results when only the percent increase is reported. In addition, some evaluations report percent increase on an annual basis, while others report it for seeded storms. One stakeholder told us reporting percent increase of precipitation due to cloud seeding on an annual basis is challenging because the number of storms seeded must be considered, and applying the percent increase from an individual storm to an entire year is inaccurate.[34] As a result, some stakeholders preferred evaluating effects by determining the amount of additional water generated.[35]

Limitations in the following areas explain, in part, some of the challenges to evaluating and interpreting the effects of cloud seeding.

Estimating baseline precipitation. The amount of precipitation that would have occurred in the absence of cloud seeding—known as "baseline" precipitation—is difficult to determine with certainty. Yet researchers need to estimate baseline precipitation to determine how much additional precipitation

[30]Andrea I. Flossman et al., "Review of Advances in Precipitation Enhancement Research," *Bulletin of the American Meteorological Society*, vol. 100 no. 8 (2019), https://doi.org/10.1175/BAMS-D-18-0160.1. WMO *Peer Review Report,* (2018).

[31]WMO *Peer Review Report,* (2018).

[32]An acre-foot is the amount of water required to cover one acre of land, or approximately one football field, to a depth of one foot.

[33]For example, if a storm was expected to produce 0.1 inches of precipitation, and cloud seeding resulted in this storm producing 0.3 inches of precipitation, then the percent increase is 200 percent. If a storm was expected to produce 1 inch of precipitation, and cloud seeding resulted in this storm producing 1.2 inches of precipitation, then the percent increase is 20 percent. In these examples, the total precipitation gain is the same (0.2 inches), but the percent increase values are different.

[34]Not all storms are seeded. Specifically, storms need to have the correct cloud conditions to conduct seeding operations. In addition, suspension criteria may prevent seeding even in storms with the correct conditions.

[35]Recent advances in instrumentation have, in part, enabled researchers to conduct such evaluations. For example, one study found that the total amount of water generated by cloud seeding ranged from 100 acre-feet for 20 minutes of cloud seeding to 275 acre-feet for 24 minutes of cloud seeding. Katja Friedrich et al., "Quantifying snowfall from orographic cloud seeding," *Proceedings of the National Academy of Science*, vol. 117 no. 10 (2020), https://doi.org/10.1073/pnas.1917204117.

is attributable to cloud seeding. Estimating baseline precipitation is challenging because precipitation varies naturally in the absence of cloud seeding, and instruments to measure precipitation may not be present in areas where the additional precipitation actually falls.

Researchers have some methods to address this challenge. For example, they can use a control—such as a cloud or area that they observe but do not seed—which they then compare with a seeded cloud or area. They can repeat such comparisons over numerous storms or conduct multiyear studies, which could lead to more precise estimates because natural variation averages out over time. However, these studies can be difficult and expensive to conduct because they may require many cases to distinguish a small effect. One stakeholder told us that the effect of climate change, such as wetter and drier periods, could complicate multiyear studies further by undermining the reliability of the estimated baseline. In addition, another stakeholder told us that controls are becoming more difficult to identify as cloud seeding operations expand, which could complicate studies that require controls in adjacent areas. Other studies attempt to track or identify seeding agents in clouds in real-time and correlate them with enhanced precipitation. However, the instrumentation used for these studies may not be available to all operators. Models might help to overcome these limitations by substituting for directly observed control clouds, but stakeholders told us these models require further research and validation.

Lack of statistically significant results. Measures of statistical uncertainty, such as confidence intervals, help to convey the amount by which estimates might vary due to randomness in the data and allow users of the estimates to assess their precision. However, in some studies we reviewed, when uncertainty was considered in estimates of cloud seeding effectiveness, the estimated effect was not distinguishable from zero with a high degree of statistical confidence (e.g., with 95 percent confidence). This is, in part, due to the high variability of natural precipitation compared to the potential effects of cloud seeding (see above). For example, while one study found an average increase in precipitation of 3 percent across 118 randomized cases, this effect was not statistically distinguishable from zero.[36] One study reported an average precipitation increase of 3 percent between 1977 and 2018 across nine cases, but the statistical results could not conclusively determine an effect from cloud seeding in seven of the cases.[37] A 2022 review paper noted that media reports, authoritative reports, and recent scientific

[36]Roy M. Rasmussen et al., "Evaluation of the Wyoming Weather Modification Pilot Project (WWMPP) Using Two Approaches: Traditional Statistics and Ensemble Modeling," *Journal of Applied Meteorology and Climatology*, vol. 57 (2018), https://doi.org/10.1175/JAMC-D-17-0335.1.

[37]In this study, seven of nine cases failed to meet the study's criteria for statistical significance, which was a p-value of less than 0.10. Matthew E. Tuftedal et al., "Precipitation evaluation of the North Dakota Cloud Modification Project (NDCMP) using rain gauge observations," *Atmospheric Research*, vol. 269 (2022), https://doi.org/10.1016/j.atmosres.2021.105996.

literature will often quote a 5 to 15 percent increase in precipitation from cloud seeding, but rarely acknowledge the statistical uncertainty associated with that increase.[38]

Estimating effects on water supplies. Additional uncertainty exists regarding the extent to which cloud seeding can ultimately improve usable water supplies. Even if baseline and additional precipitation are accurately estimated, the amount of precipitation that is lost to evapotranspiration is uncertain because of variations in climate, land surface, and vegetation coverage.[39] As a result of this and other factors, an increase in precipitation may not translate to a direct increase in water supplies. One stakeholder told us models could be used to better understand the water cycle locally and clarified that this is a challenge for the broader hydrology community, not only cloud seeding.

Uncertainties regarding health and environmental effects. Some potential benefits, especially indirect effects related to public health and the environment, may be especially uncertain. For example, while reducing air pollution by removing particulate matter could be beneficial for air quality and human health, one stakeholder expressed concerns about where pollutants washed out of the atmosphere may eventually end up. Furthermore, the uncertainty related to the resulting effect of seeding on precipitation also makes it harder to determine how much wildlife and plants benefit. For example, one stakeholder said it is not clear if cloud seeding could improve fish outcomes through higher water levels and lower water temperatures, and it is uncertain how increased soil moisture from cloud seeding might translate into healthier, less dry forests with reduced susceptibility to wildfires.

[38]Bart Geerts and Robert M. Rauber, "Glaciogenic Seeding of Cold-Season Orographic Clouds to Enhance Precipitation: Status and Prospects," *Bulletin of the American Meteorological Society*, vol. 103 no. 10 (2022), https://doi.org/10.1175/BAMS-D-21-0279.1.

[39]Evapotranspiration is the total amount of water transferred from the earth's surface and plants to the atmosphere.

3 Challenges to the Development and Use of Cloud Seeding

Using the information that we gathered from agency officials, academic researchers, industry stakeholders, and the scientific literature, we identified several challenges that can hinder the development and use of cloud seeding in ways and in situations where it may be beneficial. First, a lack of reliable scientific information and access to instrumentation for cloud seeding operations, and difficulty determining effectiveness prevent a full assessment of potential benefits and costs. In addition, uncertainty over any unintended effects of cloud seeding can lead to misunderstanding of its effect on the public. Finally, incomplete reporting of cloud seeding operational data can lead to inefficiencies in planning cloud seeding operations and hinder effective monitoring and oversight.

3.1 Lack of reliable scientific information

Uncertainty over cloud suitability. Cloud seeding operations can only enhance precipitation when the right kind of clouds are present, which limits opportunities for successful cloud seeding. It is also difficult to identify which clouds are suitable. One key attribute is that such clouds contain sufficient supercooled liquid water. But this attribute is difficult to image with radar. Modeling can help predict the presence of supercooled liquid water but may not be able to forecast its location, amount, or how long it will remain in that state. The natural variability of cloud processes adds further uncertainty to the task of selecting clouds to target. This challenge is substantial for warm season clouds that contain water in multiple phases at the same time. [40] These clouds can be seeded with glaciogenic or hygroscopic agents, but these seeding agents may interact with naturally occurring particles within the cloud in ways that are not fully understood. This interaction along with natural cloud variability makes it difficult to discern what effect the seeding had.

Climate change and air pollution may also create challenges for cloud seeding. One researcher told us that climate change may modify how seeding agents interact with clouds. Specifically, climate change has reduced moisture in the lowest part of the atmosphere, which may change cloud seeding efficacy and reduce precipitation.[41] Air pollution may also reduce efficacy by adding particles that lead to the formation of too many small droplets. Small droplets tend to remain in clouds and are less likely to form larger droplets that fall as precipitation during cloud seeding.

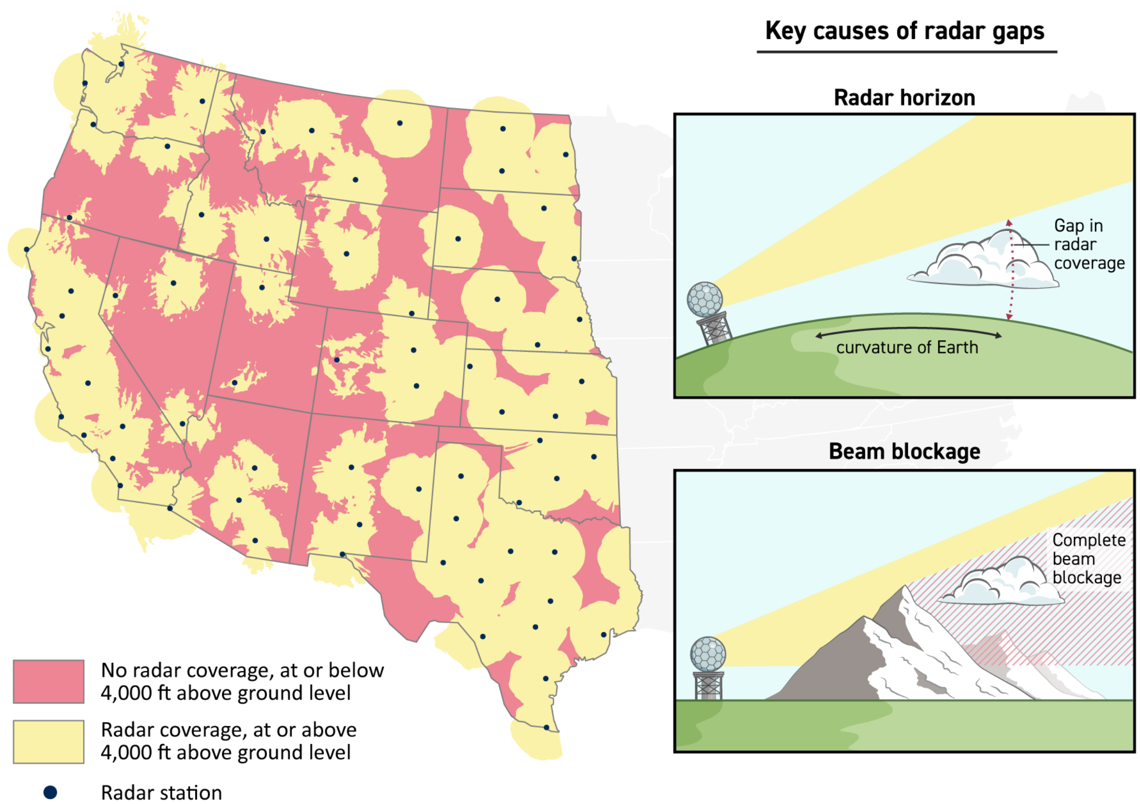
Observational infrastructure. Technologies for observing clouds—such as ground-, aircraft-, and satellite-based remote sensing—have advanced over the past

[40] Mixed-phase clouds consist of water vapor, ice particles, and supercooled liquid droplets. These components can interact over highly variable scales ranging from 100s of meters to 100s of kilometers and are not well-represented in current models. Alexei Korolev and Jason Milbrandt, "How are Mixed-Phase Clouds Mixed?" *Geophysical Research Letters*, vol. 49, no. 18 (2022). https://doi.org/10.1029/2022GL099578.

[41] Isla R. Simpson et al., "Observed humidity trends in dry regions contradict climate models," *Proceedings of the National Academy of the Sciences*, vol. 121, no. 1 (2023), https://doi.org/10.1073/pnas.2302480120.

decades, but according to an industry stakeholder, they may be too costly for local cloud seeding operators, researchers, and state government programs. According to a researcher we spoke to, Next Generation Weather Radar (NEXRAD) is the current operational infrastructure for observations, which has coverage gaps, particularly in the western U.S.[42] (See fig. 5.) Furthermore, radar is generally "line of sight" and can be blocked by mountains. Technologies such as radiometers could provide higher-quality data but are too costly to deploy widely, according to some expert meeting participants.[43] Another improvement has come from using radar and LIDAR mounted on aircraft, although mountainous terrain and cloud dynamics can make it difficult to directly observe the effects of cloud seeding on a routine basis.

Figure 5: Gaps in NOAA weather radar coverage at or below 4,000 feet above ground level, in the western U.S., and key causes



Source: NEXRAD coverage data, National Oceanic and Atmospheric Administration (NOAA); Map Resources (map outline); GAO (illustrations). | GAO-25-107328

[42]The Next Generation Weather Radar (NEXRAD) network of 160 high-resolution S-band Doppler weather radars detects precipitation and wind, and its data can be processed to map precipitation patterns and movement.

[43]Radiometers continuously measure hyperlocal air temperature, humidity, and liquid structure in the atmosphere. Much of this structure is invisible to the eye and to other remote sensing methods during cloudy conditions.

Seeding delivery. The timing and placement of seeding material is crucial in increasing precipitation. Ground-based generators are one method of dispersing seeding agents. (See figs. 1 and 2 in Ch. 1.) The ideal placement of these generators can be challenging due to issues like land ownership and access, according to researchers and an operator. Using aircraft for seeding may be more effective but also more costly. A ground-based generator may cost $50,000, according to a stakeholder. UAS are another option under consideration, but they are currently limited by FAA regulations, according to an industry stakeholder.[44] Until rulemaking is in place, a permanent UAS solution would require a combination of operating rules (that also includes operating conditions and agriculture operations) along with hazardous material dispensing and altitude waivers, according to Department of Transportation officials. For example, under FAA regulations, UAS must be operated no more than 400 feet above ground level, which may be inadequate for cloud seeding in some locations. However, Department of Transportation officials told us that they currently waive this rule up to 9,000 feet above mean sea level for one operator.

3.2 Uncertainty around unintended effects

Environmental and health effects of silver iodide and other seeding agents. Existing research we reviewed, while limited to a handful of recent studies, suggests that silver iodide does not pose an environmental or health concern at current levels.[45] However, it is not known whether more widespread use of silver iodide would have an effect on public health or be a risk to the environment. Silver iodide is nearly insoluble in water. However, when it dissolves it releases a small number of silver ions. In high enough quantities, silver ions—a known antimicrobial substance—could have harmful effects on beneficial bacteria in the environment and water resources. Other potential seeding agents—including liquid propane, other chemical salts (e.g., calcium chloride), and biological agents—are less widely used (at least in the U.S.). However, agency officials noted that new seeding agents may be subject to review by the Environmental Protection Agency (EPA).[46]

Downstream effects are uncertain. Some studies have assessed whether cloud seeding can affect precipitation outside its intended area. This research suggests a potential for downstream effects, but the extent and

[44]The regulations can be waived for applications that meet target levels of safety. 14 C.F.R. §§ 107.29, 107.31, 107.35, 107.39, 107.41, 107.145 and 107.51(b).

[45]C. Fajardo et al., "Potential risk of acute toxicity induced by AgI cloud seeding on soil and freshwater biota," *Ecotoxicology and Environmental Safety*, vol. 133 (2016), https://doi.org/10.1016/j.ecoenv.2016.06.028.

[46]Section 8 (b) of the Toxic Substances Control Act (TSCA), as amended, requires the EPA to publish and maintain a list of chemical substances manufactured or processed, including imports, in the U.S, see 15 U.S.C. § 2607(b). This TSCA inventory includes silver iodide. New seeding agents or significant new uses of existing chemicals may be subject to notification requirements and review to ensure they are manufactured and processed in a manner that protects against unreasonable risks to human health and the environment. EPA officials noted that although they do not have data sufficient to make a risk determination, the agency does not have any information to suggest that silver iodide presents or may present unreasonable risk. For more information see: https://www.epa.gov/tsca-inventory/about-tsca-chemical-substance-inventory#whatistheinventory and https://www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/actions-under-tsca-section-5#how.

direction of these effects are unclear. For example, some studies found seeding may cause a small increase in precipitation outside the target area, while others suggest a small decrease is possible—but more study is needed to quantify the effect. However, the uncertainties that limit the evaluation of cloud seeding effectiveness, described above, are even greater in non-target areas because of a lack of local observational data and infrastructure.

If cloud seeding expands, or robust calculation of the amount of water generated becomes feasible, communities may want to claim water from any cloud seeding operations that they funded, according to researchers. Currently, lower and upper Colorado River basin states fund cloud seeding in upper basin states with the expectation of overall increased streamflow downstream. Several guidelines for management of the Colorado River basin are set to expire at the end of 2026.

3.3 Data availability, perception, and other challenges

Data and reporting practices. Unreliable, incomplete, or missing data can hamper the long-term and larger-scale studies needed to measure what methods of cloud seeding are effective and in what circumstances. Without such studies, operators may be limited in their ability to enhance precipitation, and funders may hesitate to continue supporting cloud seeding operations. Operators are required to report data on cloud seeding (and other weather modification activity) to NOAA, but that information may not be complete for a variety of reasons.[47] For example, according to a state agency stakeholder, some operators may be unaware of the requirement and what information to report. Furthermore, states may require different reporting which may make the overall data on cloud seeding more difficult to evaluate or use. In addition, some operators may be reporting cloud seeding results without conducting modeling or observational studies and may report only positive results to justify their programs to sponsors, according to a researcher.

Stakeholder perception. In addition to questions about effectiveness, the public and other stakeholders may hesitate to support cloud seeding for local precipitation, potentially because they associate it with seeding for geoengineering, which aims to affect climate on longer time scales, among other reasons. As noted in Ch.1, Tennessee lawmakers recently passed a law banning cloud seeding and some other forms of weather modification operations in the state.[48] In addition, one official from Kansas told us a cloud seeding program was eliminated, in part, because of negative public perception and pressure on local officials. This state official also said that the reliance on annual funding from local sources was vulnerable to changes in public opinion regarding the cloud seeding program's value.

Understanding of best practices. Some operators may lack knowledge of or fail to adhere to cloud seeding best practices, which can reduce benefits and potentially reduce wider adoption of cloud seeding. One stakeholder told us that operators vary in

[47] 15 U.S.C. § 330a.

[48] Tenn. Code Ann. § 68-201-122 (2024).

their understanding of the environmental factors required for effective cloud seeding, such as how to target the right cloud. In addition, there is also a lack of agreement within the industry over how best to evaluate cloud seeding, according to an association we interviewed. Some contracts that do not require independent evaluations and instead use only input metrics like the number of seeding operations completed can incentivize these less-than-optimal approaches.

Furthermore, when self-evaluations are done, the operators may have a vested interest in positive outcomes such as contract extensions, according to stakeholders. A state official said that the American Society of Civil Engineers (ASCE) guidelines for cloud seeding operations are underused in cloud seeding operations.[49]

[49]American Society of Civil Engineers, *Guidelines for Cloud Seeding to Augment Precipitation*, 3rd edition, ed. Conrad G. Keyes, Jr. (Reston, VA: 2016), 234 p. https://doi.org/10.1061/9780784414118.

4 Policy Options to Help Enhance Benefits or Address Challenges

Policy options may help enhance the benefits identified in Chapter 2 or address the challenges identified in Chapter 3. For the purposes of our report, policymakers include legislative bodies, government agencies, academic organizations, industry, and other groups. We identified five policy options through a meeting with experts, our review of relevant literature, site visits, and interviews with officials in the public and private sectors. This list is not exhaustive but can provide policymakers with a broader base of information for decision-making. We have not assessed these options for their feasibility or cost effectiveness. For each policy option, we present a table with one or more potential implementation approaches, opportunities the policy option may present, and factors to consider.

Current efforts (the status quo) may address some of the challenges identified in this report. However, other challenges may remain unresolved or potential benefits may not be realized. The policy options below may help address a lack of reliable scientific information, uncertainty around unintended effects, and challenges regarding data availability, perception, and other issues.

Table 3: Policy option – Maintain status quo

This policy option may eventually address the challenge(s) of a lack of reliable scientific information and uncertainty around unintended effects:

Potential implementation approaches	Opportunities	Considerations
Policy makers could sustain current efforts to address challenges to using cloud seeding. This could include continuing to apply technologies and approaches that are already tested and commercially available.	Some current state programs may already be optimized for local conditions. Additional resources and time that may be required for other policy options could instead be used for other priorities.	Current efforts are not likely to address all challenges described in this report.

Source: GAO. | GAO-25-107328

Table 4: Policy option – Encourage targeted research to reduce uncertainty

This policy option may help address the challenge(s) of a lack of reliable scientific information and uncertainty around unintended effects:

Potential implementation approaches	Opportunities	Considerations
Government entities, researchers, and operators could promote and support research partnerships to address uncertainties.	Partnerships could enable better focus on local needs and broader questions, such as addressing fundamental cloud-physics questions while helping improve commercial operations at the local level. More research could lead to better understanding of potential environmental and human health concerns of cloud seeding. Partnerships could better coordinate research efforts and help ensure that existing research resources are better targeted and results more widely shared, helping to avoid unhelpful duplication, overlap or fragmentation of research efforts.	Cloud seeding research is best done over the long term (given the time frame over which drought occurs) but the public and policymakers often have short-term pressures and needs regarding water that drive operations toward short-term goals. New partnerships may also require more deliberate planning and consultation across sectors to identify groups that will be suited to each opportunity.
Government entities, non-profits, and scientific societies could list weather modification as a societally relevant topic (co-benefits of increasing water availability) in their research grant programs.	More awareness of potential benefits could improve use of funds for water management and understanding of equity issues with water availability.	More research may not be enough to address some uncertainties, such as indirect benefits to wildlife.

Source: GAO. | GAO-25-107328

Table 5: Policy option – Support more evidence-based operations

This policy option may help address the challenge(s) of data availability, perception, and other issues:

Potential implementation approaches	Opportunities	Considerations
Government entities and operators could ensure operations have an evaluation component through licensing and permitting requirements.	Ensuring that evaluations are done consistently across cloud seeding operations could help address data gaps and standardization challenges.	Required funding and expertise for complex evaluations may not be available.

Potential implementation approaches	Opportunities	Considerations
Government entities, researchers, and operators could improve understanding and recognition of the benefits of modeling for evaluation.	More use of modeling could improve evaluation and understanding of intended and unintended effects of cloud seeding.	Operators may lack experience and expertise with the latest models. Models may not be relevant for some specific environments.
Government entities, researchers, and operators could work together to review and potentially update suspension criteria based on local conditions over time.	Regular evaluation of climate averages could allow seeding to operate more safely in more conditions.	Reviews would require resources that may not be available.

Source: GAO. | GAO-25-107328

Table 6: Policy option – Improve monitoring and oversight

This policy option may help address the challenges of uncertainty around unintended effects, data availability, and perception:

Potential implementation approaches	Opportunities	Considerations
At the federal level, policymakers could establish a cloud seeding advisory group across relevant agencies.	An advisory group could improve coordination and increase awareness of the evidence, risks, and benefits of cloud seeding.	An advisory group at the federal level may not fully understand or incorporate local challenges. Recommendations of an advisory group may not be implemented if the agencies disagree with them or lack necessary resources.
Government entities, non-profit organizations, and commercial operators could establish a clearinghouse for information on weather modification operations.	Improving information quality and transparency could allow better public and policymaker understanding of current operations.	Collecting, maintaining, and making available such data could be a significant additional expense. Operators may not participate without a requirement to do so.
NOAA could use its authority under the Weather Modification Act to work with other government entities, researchers, and operators to update required data fields in the standard NOAA form for weather modification reporting so it reflects new technology.	NOAA's weather modification reporting form could ask for data such as specifics regarding flare constituents above a threshold and yield statistics for seeding agents.	There may be proprietary concerns about sharing some cloud seeding details, such as flare components, which would limit transparency.
NOAA could use its authority under the Weather Modification Act to work with other government entities, researchers, and operators to improve standardization of annual reports.	Standardized data collection and reporting could help establish uniformity of data, which may make research and understanding more generalizable and better support independent evaluations of cloud seeding.	Operators and researchers may vary in their ability to report information due to differences in awareness of requirements, funding, operational constraints, and the type of operations, which may have different outcome measures (e.g., hail suppression vs. rain enhancement).

Source: GAO. | GAO-25-107328

Table 7: Policy option – Expand education and science-based outreach

This policy option may help address the challenge(s) of data availability and perception:

Potential implementation approaches	Opportunities	Considerations
Federal, state, and local governments, industry associations, and operators could promote awareness of American Society of Civil Engineers (ASCE) guidelines for weather modification.	Increasing awareness of guidelines could reassure the public and policymakers concerned about the effectiveness and potential negative effects of cloud seeding operations.	Increased awareness of ASCE guidelines may not lead to using the guidelines or be sufficient to address perception challenges regarding the safety of cloud seeding.
Government entities, industry associations, scientific societies, researchers, and operators could promote awareness of the distinction between long-term climate or geoengineering applications and short-term cloud seeding to alter local precipitation.	Better public and policymaker understanding of the definitions and differences can inform debate about potential risks and benefits of cloud seeding.	Increased awareness may not address some sources of negative public perception.
State and local governments, industry associations, non-profits, scientific societies, researchers, and operators could develop communication and education strategies for weather modification that leverage existing mechanisms (e.g., broadcast meteorologists) more effectively.	Better strategies could help share existing information (e.g., suspension criteria, extreme events risk) more efficiently across sectors.	Additional resources would be required to support larger initiatives.

Source: GAO. | GAO-25-107328

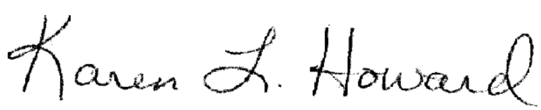
5 Agency and Expert Comments

We provided a draft of this report to the Departments of Agriculture, Commerce, Energy, the Interior, and Transportation; the Environmental Protection Agency; and the National Science Foundation with a request for technical comments. The Environmental Protection Agency and the Departments of Commerce, Energy, the Interior, and Transportation provided technical comments, which we incorporated as appropriate. The U.S. Department of Agriculture and the National Science Foundation did not have any technical comments on the report.

We also offered our expert meeting participants the opportunity to review and comment on the draft of this report, consistent with previous technology assessment methodologies. We sent the report to 14 of those experts for review and incorporated their comments as appropriate.

We are sending copies of this report to the appropriate congressional committees, the relevant federal agencies, and other interested parties. This report will be available at no charge on the GAO website at https://www.gao.gov.

If you or your staff members have any questions about this report, please contact Karen L. Howard at (202) 512-6888 or HowardK@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix V.



Karen L. Howard, PhD
Director
Science, Technology Assessment, and Analytics

Appendix I: Objectives, Scope, and Methodology

Objectives

This report examines four objectives:

(1) What are the current or emerging technologies for weather modification (including materials or processes used) and what are the most recent developments in those technologies in the U.S. and in other countries?

(2) What are the potential benefits of weather modification for the U.S.?

(3) What challenges (including health or environmental effects) could hinder or result from the development and application of weather modification technologies?

(4) To what extent are policy options warranted and what are the options?

Scope

We limited the scope of the assessment to cloud seeding and other weather modification activities that were primarily focused on inducing short-term, local changes to the atmosphere for the purpose of altering precipitation rather than longer-term approaches to modification, such as geoengineering, which are intended to induce effects that are larger in scale. To determine the appropriateness of this approach, we reviewed publicly available reports and published literature, and interviewed a cross-section of stakeholders (academia, private sector, state agencies, nonprofits, and federal agencies) in the field of weather modification to confirm that the vast majority of weather modification activities occurring within the U.S. and abroad are cloud seeding and not geoengineering. To summarize state-level cloud seeding activities, we focused on those states where cloud seeding operations were being actively conducted, funded, or overseen by the state in 2024. For the purposes of this report, we are referring to cloud seeding when discussing weather modification, unless other forms of weather modification are specified.

Methodology

To address all objectives, we used a range of methodologies. We conducted a literature search and reviewed key reports, peer-reviewed articles, and other documents. We also interviewed a range of stakeholders from across sectors involved in cloud seeding. In addition, we attended the 2024 American Meteorological Society Annual Meeting sessions focused on cloud seeding and weather modification. We visited four sites across California, Colorado, Nevada, and Texas where operations and research on cloud seeding occurs, as well as manufacturing of technology used to support cloud seeding. Finally, we held an expert meeting with representatives from stakeholder groups (see app. II). For objective 4 (in addition to the steps above), we identified five policy options, including the status quo.

Literature search

For all objectives, we reviewed relevant literature identified by agency officials, experts, stakeholders, and our literature search. We gathered additional information using a snowball technique.[50] A GAO research librarian conducted a literature search for our objectives using search terms we refined based on our review of relevant, publicly available databases, such as those maintained by the American Geophysical Union and the National Academies of Sciences, Engineering, and Medicine. The librarian also searched a variety of databases, including ProQuest Dialog Databases (Environmental Science Professional, Medical Toxicology & Environmental Health, and others), and SCOPUS. We narrowed our search to articles published since 2018 to capture recent information related to cloud seeding and other weather modification technologies. Results of these searches could include scholarly or peer-reviewed material; government reports; trade or industry papers; and association, nonprofit, and think tank publications. We selected relevant articles for further review.

Interviews

We interviewed a selection of key stakeholders with experience and perspectives on the above objectives. We identified these stakeholders from our review of literature, agency interviews, and recommendations from other interviews. Stakeholders included:

- Relevant agency officials from the Departments of Agriculture, Commerce (National Oceanic and Atmospheric Administration), Energy, the Interior (Bureau of Reclamation), and Transportation (Federal Aviation Administration), the Environmental Protection Agency, and the National Science Foundation
- Officials at four state and local agencies that conducted, funded, or oversaw cloud seeding projects
- Seven academic researchers that study cloud seeding or its effects
- Representatives from six private companies, including those that use and develop technology that supports cloud seeding
- Representatives from five nonprofits involved in cloud seeding operations, research, or policy.

Because this is a purposeful selection of the stakeholders involved in developing and using cloud seeding technologies, the results of our interviews are illustrative and represent important perspectives but are not generalizable.

Expert meeting

We convened a virtual expert meeting to inform our assessment of cloud seeding and other weather modification technologies. The meeting was held over 2 days with 16 experts that represented different stakeholder groups including those who conduct research on cloud seeding and other technologies and their uses, develop or manufacture cloud seeding technologies, or use or consider using

[50]The snowball technique involves identifying new experts, articles, or reports within those we had already reviewed on the topic or during an interview with an expert.

cloud seeding technologies. (See app. II for a list of experts and their affiliations.) We identified experts covering significant areas of our assessment from a range of stakeholder groups across sectors (federal, state, and local governments; academia; industry; and nonprofits) based on information from our interviews, literature we reviewed, web searches, and the American Meteorological Society conference we attended.

We evaluated the experts for potential conflicts of interest, which were considered to be any current financial or other interest that might conflict with the service of an individual because it could (1) impair objectivity or (2) create an unfair competitive advantage for any person or organization. We determined the 16 experts to be free of reported conflicts of interest, except those that were outside the scope of the meeting or where the overall design of our meeting and methodology was sufficient to address them, and the group as a whole was determined to not have any inappropriate biases. The comments of these experts generally represented their individual views and not the organizations with which they were affiliated and are not generalizable to the views of others in the field.

We divided the 2-day meeting into four moderated discussions on: (1) current or emerging technologies for weather modification and recent developments in these technologies in the U.S. and other countries, (2) the potential benefits of weather modification for the U.S., (3) challenges (including health or environmental effects) that could hinder or result from the development and application of these technologies, and (4) policy options that enhance potential benefits of these technologies and/or address challenges surrounding development and use of these technologies.

The meeting was professionally transcribed to ensure that we accurately captured the experts' statements. After the meeting, we reviewed the transcripts to synthesize the responses and to inform our understanding of all four objectives. We offered the participants at our expert meeting the opportunity to review and provide technical comments on a draft of our report. Nine participants reviewed our draft and we incorporated their technical comments as appropriate.

International weather modification efforts

In order to identify countries that reported conducting cloud seeding or other weather modification activities from 2020 through 2024 in Appendix IV, we used peer-reviewed literature, government reports, news articles, data provided by the Weather Modification Association and Weather Modification International, and interviews with stakeholders. For example, we considered whether a country had a research program based on whether authors within that country published findings in peer-reviewed journals. We also used the most recent comprehensive report from the United Nations World Meteorological Organization in 2018 as a starting point.[51] Then to the extent possible, we corroborated and updated information on

[51] Andrea I. Flossmann et al., *Peer Review Report on Global Precipitation Enhancement Activities,* World Meteorological Organization, (2018).

cloud seeding and other weather modification operations in those countries listed in that report using the information sources above. We were limited to English language articles, so the reported list of countries and their cloud seeding and other weather modification activities should be considered the minimum.

Policy options

We intend policy options to provide policymakers with a broader base of information for decision-making.[52] They are also not listed in any specific rank or order. We are not suggesting that they be done individually or combined in any particular fashion. We have not assessed these options for their feasibility or cost effectiveness. Additionally, we did not conduct work to assess how effective the options may be and express no view regarding the extent to which legal changes would be needed to implement them.

We developed five policy options with possible implementation approaches that could help address the challenges to development and use of weather modification technology. We then analyzed each approach by identifying potential opportunities and considerations. The policy options and analyses were supported by documentary and testimonial evidence. We offered the stakeholders at our meeting the opportunity to review and provide comments on the proposed policy options. We received comments on the proposed policy options from 10 of the 16 stakeholders, which we incorporated, as appropriate.

We conducted our work from January 2024 to December 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[52]Policymakers is a broad term including, for example, Congress, federal agencies, state and local governments, academic and research institutions, and industry.

Appendix II: Expert Participation

We convened a 2-day meeting of 16 experts to inform our work on weather modification; this meeting was held virtually on July 29 and July 30, 2024. The participants who attended this meeting are listed below. Some of these experts gave us additional assistance throughout our work, including providing assistance during our study by sending material for review or participating in interviews. In addition, 10 participants provided feedback on an early iteration of policy options. Nine reviewed our draft report for accuracy and we incorporated their technical comments as appropriate.

Darrel Baumgardner
Chief Scientist
Droplet Measurement Technologies

Derek Blestrud
Senior Atmospheric Scientist
Idaho Power Company

Bruce Boe
Vice President of Meteorology
Weather Modification International

George Bomar
State Meteorologist (retired)
Texas Department of Licensing and Registration

Rachel Cleetus
Policy Director
Union of Concerned Scientists

Jeffrey French
Associate Professor
University of Wyoming

Jonathan Jennings
President
Weather Modification Association

Dave Kanzer
Director of Science and Interstate Matters
Colorado River Water Conservation District

Darin Langerud
Director
North Dakota Atmospheric Resource Board

Rachel Licker
Principal Climate Scientist
Union of Concerned Scientists

Frank McDonough
Research Meteorologist and Director of the Cloud Seeding Program
Desert Research Institute

Daniel Swain
Research Scientist
University of California at Los Angeles

John Ten Hoeve
Acting Director, Weather Program Office
National Oceanic and Atmospheric Administration

Sarah Tessendorf
Project Scientist
National Center for Atmospheric Research

David Verardo
Acting Deputy Division Director, Division of Atmospheric and Geospace Sciences
National Science Foundation

Lulin Xue
Project Scientist
National Center for Atmospheric Research

Appendix III: Related GAO Products

GAO, *Technology Assessment: Climate Engineering: Technical Status, Future Directions, and Potential Responses*, GAO-11-71 (Washington, D.C.: July 28, 2011).

GAO, *Climate Change: A Coordinated Strategy Could Focus Federal Geoengineering Research and Inform Governance Efforts*, GAO-10-903 (Washington, D.C.: Sept. 23, 2010).

GAO, *Climate Change: Preliminary Observations on Geoengineering Science, Federal Efforts, and Governance Issues*, GAO-10-546T (Washington, D.C.: Mar. 18, 2010).

GAO, *Indemnification for Damages Provisions in Cooperative Agreement Between NOAA and Government of Australia*, B-198206 (Washington, D.C.: Apr. 4, 1980).

GAO, *Federal Weather Modification Efforts Need Congressional Attention*, CED-80-5 (Washington, D.C.: Nov. 1, 1979).

GAO, *Need for a National Weather Modification Research Program*, B-133202 (Washington, D.C.: Aug. 23, 1974).

GAO, *Cloud-Seeding Activities Carried Out in the United States Under Programs Supported by the Federal Agencies,* B-100063 (Washington, D.C.: May 31, 1972).

Appendix IV: International Cloud Seeding Activities

Table 8 is a non-exhaustive list of 39 countries we identified that reportedly engaged in any of the listed cloud seeding activities, including research and operations, during the period 2020 through 2024.

Table 8: International cloud seeding activities by country, 2020–2024

Country	Purpose	Seeding agent	Distribution	Last active year identified
Argentina	Hail suppression	Silver iodide	Rockets	2024
Australia	Precipitation enhancement, hurricane suppression	Silver iodide	Ground generators	2023
Austria	Hail suppression	Silver iodide	Aircraft	2023
Bulgaria	Hail suppression	Silver iodide, hygroscopic[a]	Aircraft, rockets	2024
Burkina Faso	Precipitation enhancement	Silver iodide	Aircraft, ground generators	*Proposed restart* 2024
Canada	Hail suppression	Silver iodide	Aircraft	2024
Chile	Precipitation enhancement	Silver iodide	Ground generators	2024
China	Precipitation enhancement, precipitation suppression[b], hail suppression, air pollution reduction, ecological protection and restoration, wildfire suppression	Silver iodide	Aircraft, cannon, uncrewed aircaft systems (UAS), ground generators, rockets	2024
Ethiopia	Precipitation enhancement	Hygroscopic	Aircraft, UAS, ground generators	2023
France	Hail suppression	Silver iodide	Ground generators	2024
Germany	Hail suppression	Silver iodide	Aircraft	2024
Greece	Hail suppression	Silver iodide	Aircraft	2024
India	Precipitation enhancement	Silver iodide, potassium iodide, hygroscopic, dry ice, liquid propane	Aircraft	2024
Indonesia	Precipitation enhancement, precipitation suppression wildfire suppression	Hygroscopic	Aircraft, UAS, ground generators	2024

Country	Purpose	Seeding agent	Distribution	Last active year identified
Iran	Precipitation enhancement	Silver iodide, liquid nitrogen, liquid propane	Aircraft, ground generators	2024
Israel	Precipitation enhancement	Silver iodide	Aircraft, ground generators	2020
Japan	Severe weather suppression (e.g., typhoons)	Not available	Not available	2024
Malaysia	Precipitation enhancement, air pollution reduction	Hygroscopic	Aircraft	2024
Mali	Precipitation enhancement	Not available	Aircraft	2021
Mexico	Precipitation enhancement	Silver iodide	Aircraft	2024
Moldova	Hail suppression	Not available	Rockets	2024
Mongolia	Precipitation enhancement, wildfire suppression, decrease desertification	Silver iodide	Ground generators, rockets	2024
Morocco	Precipitation enhancement	Not available	Aircraft, ground generators	2024
Niger	Precipitation enhancement	Not available	Aircraft	2022
North Korea	Precipitation enhancement	Silver iodide	Rockets	2020
Oman	Precipitation enhancement	Not available	Ground generators	2024
Pakistan	Precipitation enhancement, air pollution reduction	Hygroscopic	Aircraft	2023
Panama	Precipitation enhancement	Ionization[c]	Aircraft	*Proposed 2024*
Philippines	Precipitation enhancement	Hygroscopic, ionization	Aircraft, UAS	2024
Romania	Precipitation enhancement, hail suppression	Silver iodide, hygroscopic	Aircraft, UAS, rockets	2024
Russia	Precipitation suppression, hail suppression, wildfire suppression	Silver iodide, liquid nitrogen, dry ice, coarse powder	Aircraft, rockets	2022
Saudi Arabia	Precipitation enhancement, increase forestation, and decrease desertification	Silver iodide, hygroscopic	Aircraft	2024

Country	Purpose	Seeding agent	Distribution	Last active year identified
Senegal	Precipitation enhancement	Not available	Ground generators	2024
South Korea	Precipitation enhancement, air pollution reduction, and wildfire, hail, and fog suppression	Hygroscopic	Aircraft, UAS, ground generators	2024
Spain	Hail suppression	Silver iodide	Ground generators	2024
Switzerland	Hail suppression	Silver iodide	Aircraft	2024
Thailand	Precipitation enhancement, hail suppression	Silver iodide, hygroscopic, dry ice, urea	Aircraft	2024
United Arab Emirates	Precipitation enhancement	Hygroscopic, ionization	Aircraft, UAS, ground generators	2024
Zimbabwe	Precipitation enhancement	Not available	Aircraft	2024

Source: GAO analysis of peer-reviewed publications, government reports, news articles, data provided by the Weather Modification Association and Weather Modification International, and interviews. | GAO-25-107328

Note: "Not available" is used when we were unable to find details for the seeding agent or distribution method.
[a]Hygroscopic seeding includes types of salt, such as sodium chloride (NaCl), to encourage the formation of larger water droplets.

[b]Precipitation suppression is used to divert precipitation away from an area where rain is unwanted. For example, a country may induce precipitation before a storm reaches an already flooded area to avoid exacerbating the flooding or so outdoor events can take place without rain.

[c]Ionization is used to describe methods that add charged particles to a cloud to encourage the formation of larger water droplets.

Appendix V: GAO Contact and Staff Acknowledgments

GAO contact

Karen L. Howard, PhD, Director, Science, Technology Assessment, and Analytics (STAA), at (202) 512-6888 or HowardK@gao.gov

Staff acknowledgments

In addition to the contact named above, the following STAA staff made key contributions to this report:

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Katherine Chambers, PhD, Senior Physical Scientist

Miguel Cortez, Jr., General Engineer

Nathan Hamm, PhD, Senior Physical Scientist

Melanie Klein, Analyst

These staff also contributed to this work:

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