BAMS
Essay

Glaciogenic Seeding of Cold-Season Orographic Clouds to Enhance Precipitation

Status and Prospects

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ABSTRACT: This essay is intended to provide stakeholders and news outlets with a plain-language summary of orographic cloud seeding research, new capabilities, and prospects. Specifically, we address the question of whether a widely practiced type of weather modification, glaciogenic seeding of orographic clouds throughout the cold season, can produce an economically useful increase in precipitation over a catchment-scale area. Our objective is to clarify current scientific understanding of how cloud seeding may affect precipitation, in terms that are more accessible than in the peer-reviewed literature. Public confidence that cloud seeding “works” is generally high in regions with operational seeding, notwithstanding decades of scientific reports indicating that the changes in precipitation are uncertain. Randomized seeding experiments have a solid statistical foundation and focus on the outcome, but, in light of the small seeding signal and the naturally noisy nature of precipitation, they generally require too many cases to be affordable, and therefore are discouraged. A complementary method, physical evaluation, examines changes in cloud and precipitation processes when seeding material is injected and yields insights into the most suitable ambient conditions. Recent physical evaluations have established a robust, well-documented scientific basis for glaciogenic seeding of cold-season orographic clouds to enhance precipitation. The challenge of seeding impact assessment remains, but evidence is provided that, thanks to recent significant progress in observational and computational capabilities, the research community is finally on track to be able to provide stakeholders with guidance on the likely quantitative precipitation impact of cloud seeding in their region. We recommend further process-level evaluations combined with highly resolved, well-constrained numerical simulations of seasonal cloud seeding.

KEYWORDS: Orographic effects; Cloud seeding; Weather modification

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A brief history of cloud seeding to increase precipitation

Attempts at weather modification have a long and colorful history (Haupt et al. 2018). Both Zeus in the Greek mythology and the Dragon King in ancient Chinese culture are rain gods. Many ancient societies conducted elaborate rituals as a means of pleading with the gods for favorable weather. Across history, many bright minds have tried a variety of methods to enhance precipitation in the face of droughts. In the late 1940s, a robust scientific foundation emerged for the extraction of precipitation from clouds by seeding them. A period of intensive field experimentation followed, mainly in the 1950s–1980s, particularly in regions suffering water shortages, including in the western United States, Israel, and Australia (Haupt et al. 2018). These early scientific studies, many of which were published in the peer-reviewed literature, were generally inconclusive, despite claims made otherwise at the time. As early as 1964, the United States National Research Council (NRC 1964) urged caution and called for more in-depth cloud studies before initiating operational seeding programs. More high-level reports critical of weather modification followed. Research in the United States languished for three decades starting in the mid-1980s, on account of an inability to demonstrate impact on precipitation or snowpack (NRC 2003). In hindsight, we now understand that little progress was made in the 1950s–1980s due to the complexity of cloud and precipitation processes, the relatively primitive computing and observational capabilities at that time, the relatively small signal in an inherently noisy precipitation field (which implies that statistical analyses require many more cases than were collected in past experiments), and the lack of consistency in the application of otherwise well-designed statistical evaluations.

The initially supportive scientific evidence led to numerous operational cloud seeding programs. Notwithstanding the uncertainty expressed by the science community, especially in the 2003 NRC report, public enthusiasm for these programs remains high to this day. Select watersheds in many regions of the world, including in most states of the western United States, routinely are targeted for operational cloud seeding to increase precipitation (Flossmann et al. 2019). The promise of intentional weather modification has always captured the attention of the public. Certainly, the days of draconian weather control claims in the media (such as the 1954 *Collier's* magazine cover illustration "weather made to order"[1]) are long over, but even today, with more tempered expectations, public enthusiasm for weather modification persists, as evidenced by the continued media interest in this topic.

Operational cloud seeding programs are funded by a range of stakeholders, from power companies to agricultural cooperatives, and from municipal to national governments. For instance, in the face of a persistent, intense drought in the Colorado River basin (Udall and Overpeck 2017), stakeholders established a cost-sharing agreement in 2018, where lower-basin states contribute to the cost of cloud seeding in the upper-basin states (CAP 2018). In general, stakeholder interest in weather modification is largest during unusually dry spells. Cloud seeding of course requires clouds, which are less common during droughts, so more seeding impact can be expected in wet rather than dry periods.

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[1] www.novakarchive.com/vintage-magazine-covers/colliers-may-28-1954

China has a long history of weather modification at a scale much larger than anywhere else: the practice is deeply ingrained in its cultural tradition, institutionalized at all levels of government, and increasingly deployed nationwide to ascertain water security and to attempt to control natural disasters (Chien et al. 2017; Bluemling et al. 2020). Between 2012 and 2017, China spent over US$1.34 billion on various weather modification programs.[2] In 2020, China unveiled plans to develop a massive weather modification program by 2025, covering most of China (at least 5.5 million km^2, which corresponds with 58% of its land area).[3]

In the face of increasing water demand and water uncertainty in a warming climate, scientific interest in weather modification has been growing worldwide in the past 10–15 years. The 2021 International Conference on Clouds and Precipitation,[4] for instance, counted no fewer than 34 papers on weather modification from 9 countries. The United Arab Emirates have supported an international competitive research program focused on rain enhancement science since 2015.[5] Whereas two recent reviews of weather modification research (Rauber et al. 2019; Flossmann et al. 2019) almost exclusively cite sources outside China, for lack of peer-reviewed published research from China, an increasing number of China-based studies on cloud seeding research are presented at international conferences and in the English-language peer-reviewed literature (e.g., Guo et al. 2015; Chien et al. 2017). Even in the United States cloud seeding has resurfaced in government publications as a potential water supply solution, for example in a 2021 Bureau of Reclamation report on water in the Colorado River basin (Bureau of Reclamation 2021).

Glaciogenic seeding of cold-season orographic clouds

Two types of cloud seeding exist. Hygroscopic seeding involves the injection of tiny particles that absorb water easily, such as salt crystals. Droplets containing such particles grow rapidly in cloud and become large enough to collect other cloud droplets. Such seeding is designed to jump-start collisions between small droplets in clouds with above-freezing temperatures. The idea is that the hygroscopic aerosol particles help enhance droplets colliding with each other and coalescing, thus converting more of the tiny cloud droplets to raindrops that can fall to the ground. The viability of this technique to enhance precipitation is reviewed in Bruintjes (1999) and Flossmann et al. (2019). Hygroscopic seeding is beyond the scope of this essay.

Here, we focus on *glaciogenic seeding of cold-season orographic clouds*, because it is the most promising and verifiable technique to enhance precipitation. In the temperature zone between −40° and 0°C (and especially in the upper half of that zone, between −20° and 0°C) clouds anywhere on Earth often contain liquid droplets, at highly variable concentrations. When such "supercooled" droplets come in contact with ice, they freeze instantly, i.e., the supercooled liquid state is unstable. The reason why supercooled droplets commonly exist in clouds is because the freezing process requires contact with an aerosol particle with crystalline structure similar to ice (called an "ice nucleating particle" or INP), at least at temperatures above −40°C. The concentration of INPs in the atmosphere typically is much lower than the concentration of droplets in clouds, so it is not uncommon to find ice crystals surrounded by numerous supercooled liquid droplets, in so-called "mixed-phase" clouds. In such clouds, the ice crystals will grow at the expense of the droplets, because of a temperature-dependent difference in saturation vapor pressure between water and ice surfaces: liquid water is supersaturated relative to ice and will evaporate, and the vapor then deposits on nearby ice crystals. The physical mechanism of ice crystal growth in the presence of supercooled droplets was explained first by Alfred Wegener in 1911, with follow-up work by Tor Bergeron and

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[2] www.cnn.com/2020/12/03/asia/china-weather-modification-cloud-seeding-intl-hnk/index.html

[3] http://english.www.gov.cn/policies/latestreleases/202012/02/content_WS5fc76218c6d0f7257694125e.html

[4] https://iccp2020.tropmet.res.in/

[5] www.uaerep.ae/

Walter Findeisen in the 1920s and 1930s. The so-called Wegener–Bergeron–Findeisen (WBF) process is an essential process for natural precipitation across the globe.

In the late 1940s, Vincent Schaefer and Bernard Vonnegut experimented with the injection of ice-inducing (or "glaciogenic") particles into a supercooled liquid cloud, first in a cloud chamber and then from an aircraft (Schaefer 1946; Vonnegut 1947). Their experiments showed that this glaciogenic seeding increases the number of ice crystals, and that these crystals can grow at the expense of the supercooled liquid water (SLW) and fall out. Much of the enthusiasm for weather modification in the 1950s–1980s can be traced back to their work. The most commonly used seeding agent is silver iodide (AgI), because AgI nuclei act as INPs at relatively high temperatures. That is because solid AgI has a crystalline structure very similar to that of ice. Other glaciogenic agents or methods are used as well (Flossmann et al. 2019; Ćurić et al. 2019). In particular, liquid or solid CO_2 can be injected into clouds to locally briefly cool the air to −80°C. This will locally induce homogenous freezing of droplets in cloud, as opposed to heterogenous, or aerosol-mediated, freezing. The resulting ice crystals may then grow through the WBF process. Schaefer and Vonnegut experimented by dropping pellets of dry ice (solid CO_2) into a cloud from aircraft. This is the same dry ice one can purchase in grocery stores to keep frozen foods cold. The photos in Schaefer (1946) and Vonnegut (1947) showing the clearing of clouds along their flight tracks were convincing to many at the time and are still used in some meteorology textbooks today (e.g., Lutgens and Tarbuck 2013), but their experiments were not well constrained: ice crystals could have been induced in the low pressure zones behind the tips of the aircraft's propellors (Rangno and Hobbs 1983; Heymsfield et al. 2011), and clouds could have been cleared by the downwash in the wake of the aircraft's track.

The hypothesis driving glaciogenic seeding is that natural precipitation is limited by the number of INPs in clouds and that precipitation can be increased by dispersing INPs into clouds containing SLW, such that newly created ice particles can grow, gain fall speed, and reach the ground as additional precipitation. Glaciogenic seeding of cold-season orographic clouds is conducted in most states in the western United States, as well as in Australia and China, among other countries. Several countries across the world have glaciogenic seeding programs that target thunderstorm inflows, either to enhance precipitation or to suppress damaging hail. That practice, first proposed by Kraus and Squires (1947), is beyond the scope of this essay. The reason is that observational isolation of the effect of seeding is far more difficult for thunderstorms than for cold-season orographic clouds [the latter vividly illustrated in French et al. (2018)]: the variability between individual cumulonimbus clouds is much larger than the expected seeding signal, so the control group has unwieldy diversity. And thunderstorm evolution is sensitive to local ambient conditions that are virtually impossible to adequately measure (e.g., local flow patterns and humidity variations near the ground), so attribution to seeding is extremely difficult.

The scientific basis for glaciogenic seeding of cold-season orographic clouds to enhance precipitation

Is supercooled water abundantly present in cold-season orographic clouds? Recent reviews of glaciogenic seeding of orographic clouds can be found in Rauber et al. (2019) and Flossmann et al. (2019). These in-depth reviews have two things in common. First, they cite observational and modeling evidence that *SLW is commonly present in cold-season orographic clouds*. Given that shallow orographic clouds occur in predictable locations (over and just upstream of mountains), and given that mountains are naturally the main source of water in dry climates (especially in colder or higher-elevation watersheds where precipitation mostly falls as snow, contributing to the seasonal snowpack), these clouds are prime targets for glaciogenic cloud seeding. A practical challenge is that the boundary layer in the valleys upstream of target mountain watersheds often is stably stratified in the cold season, such that AgI nuclei released from ground-based generators often do not mix with the orographic SLW layer. When these "blocking" conditions are present, aerial release of the seeding material is likely more effective, e.g., from an aircraft.

The *observational* guidance for precision seeding remains sparse. Passive microwave radiometers have long been used in seeding operations to detect liquid water (e.g., Heggli and Rauber 1988). A radiometer primarily estimates total liquid water in an atmospheric column, i.e., the vertically integrated amount, known as the liquid water path. The 3D cloud liquid water distribution cannot be measured. Precipitation, on the other hand, can be measured at much finer spatial resolution, with radars. Unfortunately, weather radars are unable to detect SLW, because that water generally is found in small droplets only, too small for the radar to detect. This even applies to millimeter wave "cloud" radars in a mixed-phase cloud: ice particles (even in small concentrations) will dominate the radar return.

There is observational evidence from aircraft measurements that SLW is commonly present in clouds on the upwind side of terrain ridges in winter storms. This is because under strong unblocked flow, a mountain ridge produces a significant stationary updraft, resulting in rapid cooling and condensation of water vapor. Winter storms crossing mountains typically also contain transient, strong updrafts. Because condensation and evaporation respond immediately to ascent and descent, respectively, the presence of transient updrafts suggests that the orographic SLW distribution probably has a significant small-scale, transient component as well. This has long been confirmed by radiometer data (Rauber and Grant 1986; Sassen et al. 1986; Huggins 1995) and supported by model simulations (e.g., Chu et al. 2017). Because such transient SLW pockets cannot be anticipated, ground-based seeding operations usually disperse the seeding agent for the duration of a storm, with the expectation that the seeding plumes will blanket periods of high SLW (e.g., Mazzetti et al. 2021). In essence, variability in SLW makes precision targeting of regions of high SLW content very difficult.

Seeding operations can benefit from *model guidance* predicting the likelihood of SLW. High-resolution cloud-resolving weather prediction models are currently used in some operations to help with decisions such as seeding period, selection of ground-based generators, and optimal flight level for aerial seeding.

Cloud and precipitation processes must be *parameterized* in a numerical weather prediction model, because they occur at scales far too small to resolve. For instance, cloud water in the form of small droplets (which do not fall out) results from the condensation of vapor, which occurs when a rising air parcel becomes overly supersaturated in the model. When too much cloud water accumulates at a grid point, a *parameterization* ensures that some of these small cloud droplets are converted to rain, which can fall out. Cloud microphysical parameterizations are built on basic physical processes and have become quite complex and increasingly realistic. While the computational cost of sufficiently resolved models (horizontal resolution ~2 km or better) is becoming increasingly affordable, SLW content remains one of the most difficult variables to numerically predict, with large discrepancies between different cloud and precipitation parameterizations that can be applied in models. Much uncertainty remains in prediction of SLW, because parameterizations are normally validated in terms of the resulting precipitation (which is measured extensively), not SLW content (which is rarely measured).

Can glaciogenic cloud seeding substantially increase surface precipitation? The question remains whether well-targeted cloud seeding increases surface precipitation in an economically viable and beneficial way. That brings us to the second point of agreement in the reviews by Rauber et al. (2019) and Flossmann et al. (2019): they both argue that while numerous studies point to a positive impact (i.e., seeding enhances precipitation), *uncertainty remains, and quantitative impact assessment remains a challenge*. Confirmation of the value of cloud seeding to society requires evaluation of two complementary questions: is a positive impact verifiable, and is it sufficient to be economically viable and beneficial? Two types of studies have been conducted to quantify the precipitation impact: *randomized seeding experiments*, examining precipitation in a control and a target region, borrowing statistical approaches to evaluation from disciplines such as medicine, and *physical evaluations*, examining the direct chain-of-effect cloud microphysical and dynamical processes that result following the injection of seed material in a cloud. The two methods are complementary: the former focuses on the outcome (quantitative precipitation estimation), whereas the latter focuses on processes and thereby provide insights into environmental conditions most suitable for seeding. We discuss both types of impact assessment studies next.

Randomized seeding experiments. Many randomized experiments were conducted in the 1960s–1980s, to confirm the hypothesis that seeding enhances precipitation. While these experiments were based on sound statistical principles, several follow-up studies have questioned the validity of the published results of these experiments, e.g., because of data selectivity, a posteriori definition of the control area, or lack of control area altogether. Details can be found in Rauber et al. (2019) and Flossmann et al. (2019). In our opinion, these early experiments were both technologically ill equipped and too short to obtain statistically significant results. Even if they were deemed statistically significant, they could not prove the overall validity of the assumed underlying physical process. These early experiments were unable to collect sufficient cloud information (e.g., cloud top temperature, SLW layers, convective activity, etc.) to support any statistical outcome. Fundamentally, they underestimated (i) snowfall measurement uncertainty, (ii) the variability of natural precipitation rates, i.e., the inherently chaotic nature of precipitation, and (iii) the variability of clouds' sensitivity to seeding. These three factors make seeding impact demonstrations particularly challenging. The implication of the second factor is that storm total and even seasonal precipitation decorrelate rapidly with distance, such that a significant uncertainty is introduced for control stations located at a distance sufficiently large not to be impacted by seeding intended for the target area. The larger the natural variability, the more difficult it is for a statistical evaluation to detect the seeding signal from the background noise, and the more cases are needed. An estimate of the threshold number of cases is based on an a priori assumption of the magnitude of seeding signal.

For instance, the experimental design of one of the more recent and rigorous randomized experiments to date, the Wyoming Weather Modification Pilot Project (WWMPP; Breed et al. 2014), called for 100–150 cases, assuming a seeding signal of 15%–20% precipitation enhancement in seeded storms. In this scenario, the 118 cases collected over 6 years (2008–13) would have been statistically sufficient to reject the null hypothesis that there was no effect from ground-based cloud seeding (Rasmussen et al. 2018). The actual seeding effect appeared to have been much smaller and would have required many more cases (over 1,000 cases, to be collected over many more years) to show that cloud seeding had a statistically significant effect.

The sample size for another recent randomized experiment using ground-based seeding, the Snowy Precipitation Enhancement Research Project (SPERP; Manton et al. 2011; Manton and Warren 2011; Manton et al. 2017), was about the same (107 cases over 5 winters). The environment over the Australian Snowy Mountains was very different, with much warmer cloud bases than in Wyoming. Both SPERP and WWMPP recorded a positive change in gauge-measured precipitation, although below their a priori significance level. Both Manton et al. (2017) and Rasmussen et al. (2018) refer to the difficulty of accurate snowfall measurement, especially under the windy conditions typically observed in the target areas. *The large number of cases needed to establish statistical significance in the face of a relatively small seeding effect* *renders most randomized seeding experiments too costly and too time consuming*. In addition, such experiments provide no insight in optimal seeding conditions. Therefore, the community has moved toward performing cloud seeding evaluations in a physical manner, with detailed cloud observations and enhanced computer modeling, as discussed next.

Physical evaluations. Much progress has been made in recent years through *physical evaluations* (Rauber et al. 2019), combining targeted measurements using novel instruments such as cloud radars with numerical simulations of natural and seeded cloud processes, as in the 2017 Seeded and Natural Orographic Wintertime Clouds: The Idaho Experiment (SNOWIE; Tessendorf et al. 2019). SNOWIE studied the cloud-microphysical processes in aerially released plumes of AgI with radar and airborne in situ cloud measurements. SNOWIE research was sponsored by the United States National Science Foundation (NSF). The experiment piggybacked on a long-term operational seeding program conducted by the Idaho Power Company, Inc. (IPC). Unambiguous attribution of precipitation enhancement was possible in three SNOWIE cases. Very little natural precipitation occurred in these three cases, and sufficient SLW was present, such that AgI-induced snow growth was obvious on radar as lines of enhanced reflectivity downwind of the seeding aircraft (French et al. 2018). Similar signatures in SLW clouds have been observed elsewhere (e.g., Wang et al. 2021), even in operational radar reflectivity imagery. Friedrich et al. (2020) quantified the surface precipitation resulting from the radar-detected snow plumes in the three SNOWIE cases: the total amount of water generated by cloud seeding ranged from 1.2×10^5 m^3 (100 acre feet) for 20 min of cloud seeding to 3.4×10^5 m^3 (275 acre feet) for 24 min of cloud seeding in these cases. Idaho Power has long collected measurements of precipitation and silver-in-snow (from AgI) in and around their target watersheds, in an attempt to quantify the impact on the seasonal snowpack, and it uses the results of this ongoing research to justify its seeding operations. IPC was a natural partner for the NSF-funded SNOWIE research because the company sought more confidence in its seeding impact and more scientifically based guidance in its seeding decisions.

As mentioned earlier, cloud and precipitation processes are parameterized in weather models, such as the widely used, publicly available Weather Research and Forecasting (WRF) Model. Xue et al. (2013a,b) built a module (called WxMod) on top of one of the cloud schemes available in WRF to simulate the interaction of AgI nuclei with clouds, such as their absorption in droplets, the subsequent droplet freezing, and the resulting snow crystal fallout onto the ground. Xue et al. (2022) used the WxMod module to numerically reproduce not only the essential natural cloud conditions for one of the three SNOWIE cases mentioned above, but also the seeding effects on precipitation (approximate amount and impacted area). Case-specific model validations are hindered by the uncertainty in initial and boundary conditions. In fact, Xue et al. (2022) first had to adjust the upstream wind profile in order to reproduce the observed natural cloud structure. This initial value uncertainty decreases with the number of cases, as in a seasonal simulation. In many of the SNOWIE cases, natural precipitation was occurring at the same time as seeding. Analysis of these cases is ongoing as the seeding signature could have been masked by the natural variability in radar echoes or in ice particle number concentrations (which were measured with flight-level cloud probes).

Tremendous progress has been made in recent years with the numerical simulation of orographic precipitation, mainly because of advances in computational resources. For instance, Xue et al. (2022) uses extremely fine grid spacings (100 m in the horizontal, and 43 levels in the lowest 3 km above the ground) such that the details of the terrain and large boundary layer eddies can be resolved (so-called large-eddy simulations, or LES). The seeding impact in this case was similar for a less computationally demanding simulation at ~1 km resolution, in which the boundary layer processes are parameterized. Such simulations can be run for all seeding events in a season to quantify the cumulative precipitation impact of an operational seeding program.

Uncertainties remain in the representation of natural aerosol, cloud, and precipitation processes and in the pathways of the AgI nuclei through the cloud system, including the 3D dispersion of seed material released from the ground or an aircraft. To better constrain the simulations, field campaigns such as SNOWIE are essential, in order to detail meteorological, aerosol, and cloud conditions. As a minimum, well-calibrated radiometric measurements of SLW should be routinely collected, so that models can be evaluated over the full range of weather conditions. In summary, much progress has been made with physical evaluations, such that we now have, for the first time, *a robust, well-documented scientific basis for glaciogenic seeding of cold-season orographic clouds to enhance precipitation*. But more work is needed before *a robust observationally validated assessment of the impact of seeding on seasonal precipitation and the snowpack can be made*.

Public acceptance of cloud seeding

Cloud seeding may appear esoteric to people living in wet climates, but in dry regions, it remains a hot topic, certainly among those concerned about water availability. Water concerns loom especially large in the Colorado River basin, where reservoirs were at historically low levels in late 2021.[6] The question naturally raised by decision-makers is whether operational cloud seeding can alter the seasonal water balance of a basin sufficiently through a cold season to impact water supply in a cost-effective manner. Local governments and stakeholders generally support operational cloud seeding, especially during periods of drought, so effectively, they answer this question affirmatively. The most-commonly voiced public concern is not about cloud seeding effectiveness, but rather about seeding operations "stealing" precipitation from downstream areas (Mulvey 1977; WMA 2013; DeFelice et al. 2014). The uncertainty for downstream areas is at least as large as that for target areas.

Media reports often quote the quantitative precipitation impact estimates provided by seeding operators. Quotes typically range between 5% and 15% (WMA 2013), and often higher, with little acknowledgment of uncertainty. Such quotes were commonly found in the 1950s–1970s, both in authoritative reports (e.g., Thom 1957) and in experimental studies (many of them flawed, as discussed above). They can be found even in some recent scientific literature (e.g., Wu et al. 2018; Wang et al. 2019). Unfortunately, these statements lack a specific basis of reference: is it during a single seeding event? Is it the average increase in any storm? Does it apply only to the targeted storms, based on some seeding criteria? Since seeding operations normally last the entire cold season, the relative change in precipitation should be expressed as a fraction of the total seasonal precipitation. This includes precipitation from storms that are not seeded because they do not meet the seeding criteria, which may be a substantial fraction (e.g., Ritzman et al. 2015). In addition, quotes of relative increase in precipitation without the caveat of uncertainty should be avoided, because none of the statistical or physically based studies to date have been able to firmly quantify the full seeding impact, be it for a single event or for a season of events or for ground-based or airborne seeding. Even the estimates for the abovementioned SNOWIE cases (Friedrich et al. 2020) are somewhat uncertain, given radar scanning and reflectivity-based precipitation rate estimation limitations.

Public sector managers involved with cloud seeding cannot be expected to follow all the scientific literature on the topic, although some, such as those at IPC, work very closely with scientists in assessing seeding operations. In several public meetings attended by one of the authors, stakeholders have stated that much scientific progress has been made in recent years and that unambiguous attribution of precipitation to seeding now has

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[6] https://earthobservatory.nasa.gov/images/148861/lake-powell-reaches-new-low

been made (referring to SNOWIE in particular). These statements are valid. But then, some stakeholders still quote precipitation increments of 5%–15%. Such quotes appear to stick. That brings us back to the question of what explains the public's confidence in the effectiveness of cloud seeding. To our knowledge, recent weather modification reporting in the news media reflects the uncertainty voiced by scientists, at least in recent times.[7] We admit that there is some misinformation in the media, but ultimately the public's confidence may be rooted in a hope for a solution to ongoing water shortages, and a belief that humans have the technology to alter natural processes. Such attitude may discourage investment in infrastructure intended to improve seeding effectiveness and impact evaluation (such as radiometers and disdrometers). The burden is on the scientists to communicate more effectively with stakeholders and the public: hence this essay.

Recommendations for further progress

Precipitation impact estimation through physical process studies. The main message of the above brief survey of the current state of cold-season orographic cloud seeding science is that quantification of precipitation change due to seeding is difficult, but *progress is possible through physical process studies*. Robust randomized seeding experiments require more time and money than can ordinarily be afforded. Few in-depth, case-study-based physical evaluations with airborne and ground-based radar and in situ precipitation sensors have been conducted. As mentioned above, published SNOWIE research to date has focused on low-hanging fruit, i.e., three essentially nonprecipitating cases where the seeding impact was evident on radar. Combined modeling–observational work now is in progress to tease out a seeding impact in other cases, but quantitative precipitation impact estimation will remain less certain than the three cases without substantial natural precipitation. The SNOWIE campaign revealed a range of SLW amounts, flow patterns, moisture and stability stratifications, and updraft structures at a range of scales, all of which influence orographic precipitation as well as the cloud response to seeding. Certainly, the full parameter space was not captured by the 18 airborne seeding cases examined in SNOWIE, and SNOWIE captured conditions in just one particular watershed. For instance, proximity to the ocean may well be important as the background aerosol content of a marine boundary layer is very different from a boundary layer impacted by a city, a forest, or a desert. Given the higher SLW typically found in coastal orographic clouds, compared to clouds over interior ranges, it is quite possible that the seeding impact is larger over moist coastal ranges than over interior mountains, where the boundary layer contains far less water vapor and measured SLW concentrations typically are low (e.g., Mazzetti et al. 2021).

Recommendation 1: We recommend more physical process studies, with glaciogenic seeding examined in the context of fundamental cloud microphysical questions (e.g., about ice nucleation), using novel instruments, laboratory studies, and state-of-the-art numerical simulations. Novel technologies include 3D holographic cloud imaging systems, radars at multiple frequencies, polarization backscatter lidars that can detect SLW, and scanning microwave radiometers that better resolve the vertical structure of the SLW. A dense network of ground stations with probes such as precipitation gauges, disdrometers, and profiling radars can be deployed over the course of a season. Multisensor retrievals based on data from radars, lidars, and radiometers can be used to estimate ice particle number concentrations, ice water content, and liquid water content. Novel modeling techniques such as those used recently in support of SNOWIE (e.g., Xue et al. 2022) can be refined to quantify the seeding impact.

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[7] Here is a sampling of 2021 media reports on cloud seeding: https://subscriber.politicopro.com/article/eenews/1063727525; https://subscriber.politicopro.com/article/eenews/1063727677; www.theguardian.com/environment/2021/mar/23/us-stated-cloud-seeding-weather-modification?utm_term=dc89ea8c1e08522ebbbab21ea9cd5b41&utm_campaign=GuardianTodayUS&utm_source=esp&utm_medium=Email&CMP=GTUS_email; www.byuradio.org/TOP-2021-04-13-Cloud-Seeding; www.youtube.com/watch?v=md2ubLeeb4k; https://grist.org/climate/can-cloud-seeding-help-quench-the-thirst-of-the-us-west/.

Interests in weather modification half a century ago led to an explosion in fundamental cloud and aerosol physics research, which advanced numerical weather and climate prediction. In turn, the rich array of observational and numerical tools developed more recently to study weather and climate can be used to further reduce cloud seeding uncertainties.

Feasibility of cost–benefit analyses. Novel measurement and computational capabilities have significantly advanced the scientific analysis of orographic cloud seeding to a point where *cost–benefit analyses have become more feasible*. Seeding operators commonly argue that even if the precipitation increase is just 1%, seeding is worth the cost, but that depends on market conditions. The cost of seeding operations is generally well known, but the benefits are hard to quantify, and may be multiple. For instance, IPC manages a long-term aerial and ground-based seeding program in several watersheds in Idaho to enhance hydroelectric power production. Any extra water generated by IPC's seeding program benefits not just its hydropower system, but also many other water users including agriculture, fisheries, industries, and cities. In Idaho, some of these external users contribute to the cost of the seeding program. The main uncertainty remains the seasonal amount of extra water.

Uncertainty resides not just in the quantitative precipitation enhancement, but also in processes at the land surface (the snowpack and the soil), below the soil, in streams and in reservoirs: some of that extra precipitation will support a forest ecosystem, some will evaporate, and a poorly understood fraction will find its way through hydroelectric power systems or irrigation ditches. It has generally been assumed that for small watersheds the fractional increase in seasonal streamflow is the same as the fractional increase in seasonal precipitation, but that may not be the case. Much effort is underway (unrelated to cloud seeding) to better understand the complex snowpack, land surface, vegetation, and surface/subsurface hydrological processes in watersheds, and to represent these processes in physical models, such as WRF-Hydro, in order to better predict seasonal streamflow. Recent progress in this area is impressive: this complex chain of processes now can be captured by coupled numerical models that resolve the detailed orographic flow, clouds and precipitation, snowpack dynamics, the land surface, and ultimately the streamflow, although significant uncertainties in hydrological modeling remain, especially regarding the subsurface flow.

Recommendation 2: In order to quantify benefits, we recommend highly resolved, well-constrained seasonal cloud seeding simulations coupled with land surface and hydrological models. Such simulations are rather novel and need to be thoroughly vetted. Uncertainties will remain. They can be narrowed through dedicated, targeted observational campaigns. Uncertainties can be estimated through an ensemble of simulations, each with slightly different model boundary conditions, boundary layer, cloud, and seeding parameterizations, as well as different land surface and hydrological schemes.

Conclusions

A robust assessment of seeding efficacy and impact on streamflow requires complex, coupled modeling systems able to reliably estimate seasonal precipitation and cloud seeding impact. While significant progress has been made, these types of modeling systems need to be validated under a broad parameter space, and that calls for more comprehensive, targeted measurements. Our two recommendations are consistent with those made in the 2003 NRC report. Process-focused physical evaluations with detailed field observations to enhance and evaluate numerical simulations have been proven to be effective through public–private partnerships. While commercial seeding programs should collect more observations (e.g., from radiometers), they cannot be expected to support field campaigns with advanced observational technologies: support from governmental funding agencies is needed, something agencies in the United States and elsewhere have been reluctant to do (NRC 2003), until recently.

The ongoing synergetic relation between IPC, the National Center for Atmospheric Research (NCAR), and universities serves as an example for this type of effort. It enabled the NSF-funded observational campaign (SNOWIE), an improved understanding of physical processes under natural and seeded conditions, and the development, testing, and further refinement of the WxMod model by NCAR. The SNOWIE campaign would not have been possible without IPC's airborne seeding and measurement infrastructure on the ground, and in turn, through the published SNOWIE research, IPC has gained confidence in its operational seeding program and in the WxMod model, to guide further seeding decisions and to quantify seasonal seeding impact on the snowpack. Further synergistic research of this kind will improve understanding of the environmental, cloud, and background aerosol conditions most suitable for seeding. This, together with the high-resolution predictive simulations that operators now typically run to guide their seeding decisions, in turn will result in more surgically precise operational cloud seeding. Through this *synergetic process of targeted research-quality observations and high-resolution simulations in the context of operational seeding programs, precipitation enhancement will become quantifiable with an increasing degree of certainty*.

Therein lies the hope for a substantial narrowing of the seeding efficacy uncertainty through a process of continued vetting and improvement of model representation of cloud microphysical processes resulting from cloud seeding. Some seeding operations may prove to be economically unviable. Other programs may prove cost-effective and may see yield increases and cost reductions from better observational and model-driven guidance about the location and timing of ground-based or aerial AgI dispersion activities. The benefit may be lower in relatively arid places, but the value of water is higher there. At this time, we neither encourage nor discourage ongoing operational glaciogenic seeding of orographic clouds. For some operators, the currently available, limited evidence may be sufficiently compelling notwithstanding the uncertainty. We do encourage the pursuit of well-designed ensemble seeding impact simulations covering at least one season, be it for past seeding operations or for future feasibility purposes. And we encourage the collection of detailed measurements of cloud and environmental conditions to improve model parameterizations and to enable increasingly reliable estimates of the impact of seeding on seasonal precipitation, snowpack, and streamflow.

Water supply uncertainties are expected to grow in a globally warming climate. The time is right to reduce the persistent uncertainties associated with cloud seeding to enhance precipitation, using observational and modeling capabilities that only recently have become available.

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