Chapter 2
Rain Enhancement Through Cloud Seeding

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Abstract An increasing number of countries are planning to carry out rain-enhancement activities in response to water shortages and other societal needs. Rain enhancement can work with reasonable cost–benefit ratios under the right conditions. However, many components of the technology need improvement and testing, and many physical processes are not yet fully understood due to their complexity. Global research on cloud-seeding technology indicates that precipitation can be increased up to 15% of the annual norm, depending on the available cloud resources and technical systems used. However, there is still ambiguity in the results of the studies conducted and the effects and scale of the rain enhancement. When evaluating the results of rain enhancement projects, it is necessary to adhere to rigorous scientific approaches and proven methods.

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2.1 Introduction

The Earth's atmosphere contains about 13,000 km^3 of water in the vapor phase, the source of which is evaporation from the surface of the oceans, seas, soil moisture, and transpiration from plants. These water-vapor reserves are continuously renewed due to the circulation of evaporation–condensation and precipitation, making eight to nine hydrological cycles annually (Bengtsson 2010). Thus, the water vapor present in the atmosphere is an infinite freshwater source and an opportunity for rain enhancement (RE).

Cloud seeding (CS) has been used for more than 75 years for the purpose of RE, hail suppression (HS), fog dispersion, and the improvement of weather conditions. Under pertinent conditions, CS involves the application of extensive technology for the modification of the precipitation regime in convective clouds, large-scale stratus clouds, and ground fogs, by dispersing special glaciogenic or hygroscopic substances within clouds or in their vicinity. These particles enable water droplets or ice crystals to activate on heterogeneous nuclei through water-vapor condensation–freezing processes (Flossmann et al. 2019). Subsequent collision–coalescence growth of water droplets and ice crystals leads to the formation of large rain-sized hydrometeors (drops, graupels, hailstones, snowflakes, etc.) that fall as precipitation.

Some estimates show that only up to 10–15% of the total cloud water content of typical cumulonimbus convective clouds is released to the ground as precipitation, while the rate of precipitation from these clouds varies in the range of 10,000 to 50,000 t/min (Abshaev et al. 2009), a number that exceeds the capacity of all currently operational desalination plants (Eke et al. 2020) and suggests the huge potential of RE technologies.

This chapter focuses on rain enhancement through CS and provides concise information on: the basics; a variety of technical options for its execution; and on unresolved scientific aspects. The main objective is to briefly convey to the reader the potential and the limitations of CS methods for addressing global water scarcity. A major part of the chapter stems from a report of the World Meteorological Organization (Flossmann et al. 2018), which was funded by the United Arab Emirates.

2.2 History

For thousands of years, people have sought to modify weather and climate to increase water resources and mitigate severe weather. Aristotle was already able to formalize the observations of weather accumulated by the 3rd century BC, which gave meteorology the status of a science (Burtsev et al. 2018). From his work, even in those days, he was studying the mechanisms of precipitation, particularly that of hail.

The modern technology of weather modification (WM) was launched by the discovery in the late 1940s that supercooled cloud droplets could be converted to ice crystals by the insertion of a cooling agent such as dry ice or an artificial ice nucleus such as silver iodide (AgI). About 80 years of subsequent research has greatly enhanced our knowledge about the microphysics, dynamics, and precipitation processes of natural clouds (rain, hail, snow) and the impacts of human interventions on those processes (Rauber et al. 2019).

The main obstacle has always been the need for enormous amounts of energy to manage meteorological processes. For example, the energy associated with the formation of convective clouds is equivalent to several of the largest hydroelectric power plants. If we want to change the direction of the wind within a 100-km region, then we would need to use energy generated by all the power plants in the world. Moreover, if we decided to change the weather of a territory or a small country, the current total global energy generation would not be sufficient.

However, in addition to the enormous energy needs, the unstable state is necessary to govern different evolutionary processes that are favorable through small impulses in the meteorological processes. In other words, the only credible approach to modify weather is to take advantage of microphysical and dynamic sensitivities through human interventions. It is assumed that a relatively small human-induced disturbance in the system can substantially alter the natural evolution of atmospheric processes. Currently, there are three instability states in clouds that are being utilized by human interventions; (1) Colloidal instability, which is a condensation–coagulation growth of droplets in clouds and rainfall from warm clouds; (2) thermodynamic (liquid–ice phase) instability of colloidal systems in clouds and fogs containing supercooled water; and (3) convective instability of the atmosphere.

The scientific basis of WM depends on the understanding of how clouds composed of tiny droplets evolve into precipitation. One principal path is provided by the fact that the ice particles in the presence of supercooled cloud drops can constitute a nonequilibrium state that results in the growth of the ice and evaporation of the drops. The German meteorologist Alfred Wegener was the first researcher who addressed WM (Wegener 1910, 1912). Later in 1933, the Bergen school meteorologist Tor Bergeron at the Lisbon meeting of the International Union of Geodesy and Geophysics developed the argument that relatively few ice particles in a supercooled cloud could individually grow large enough to provide a release as precipitable particles. Bergeron's hypothesis that rain can have its origin in snowflakes was a cornerstone for cloud physics. The acceptance and rapid further development of this hypothesis was greatly advanced by the work of another German scientist Walter Findeisen (1938) and others contributing to the theoretical development of cloud physics and its application to WM in the 1940s and 1950s (Al Mandous et al. 2006).

In the former USSR, the basis of condensation growth of particles was developed through experimental/theoretical studies of precipitation-formation processes in clouds and coagulation phenomena and studies in the microstructure of clouds and precipitation, obtained in the early 1930s at the Leningrad Institute of Experimental Meteorology under the supervision of V.N. Obolensky. Later, the first data on the water content and the size of droplets in clouds were obtained, and empirical and numerical models of clouds were created at the Voeikov Main Geophysical Observatory, using aircraft meteorological laboratories. This new knowledge about the processes taking place in cloud systems made it possible to construct a concept of the increase in liquid precipitation based on an artificial increase in the concentration of crystallization nuclei in a cloud. To check and clarify the provisions of the concept, a technically equipped experimental test site was created. As a result of research and development work of scientific teams of the former-USSR National Hydrometeorological Service, reagents that can be dispersed have been developed and used as artificial crystallization nuclei and, in some cases, as condensation nuclei. Further research was conducted on methodological techniques and technical means for bringing them into clouds, as well as the development of criteria to assess the degree of readiness of the cloud to produce additional precipitation (Burtsev et al. 2018).

In 1946, Vincent Schaefer demonstrated that dry ice dropped into supercooled clouds rapidly transformed the droplets into ice crystals. The same effect at cloud temperatures below −10 °C was demonstrated by his colleague Bernard Vonnegut at the General Electric Laboratory using AgI particles in 1947. These experiments were carried out under the direction of Nobel Laureate Irving Langmuir, who was also instrumental in promoting a five-year series of field experiments (Langmuir 1950). Those experiments, plus similar experiments carried out during the same year, yielded convincing visual proof that cloud-seeding induced changes in cloud composition depth and other characteristics can be readily achievable. Experiments and CS operations commenced all over the world and many continue to this day. The precipitation-forming processes in clouds from which substantial amounts of precipitation might be expected are much more complex than the simple ones where visible evidence of seeding might be provoked. Thus, it has proven to be a much greater challenge to quantify microphysical seeding signatures and to obtain statistical documentation of added precipitation on the ground. Each of the two has been achieved separately, but their combination, which is necessary for maximum scientific credibility, has not yet been fully achieved. It was found, however, that the energy involved in weather systems is so large that it is impossible to create entire artificial rainstorms or to alter wind patterns to transport water vapor into a region.

In the mid-latitudes, hail damages exceed three billion dollars per year worldwide, and for many countries HS is an attempt to reduce economic damages in agriculture. Reduction of hail damage by CS became a major part of WM activities after the introduction of the concept of *"beneficial competition"* (Sulakvelidze et al. 1965) at the High Mountain Geophysical Institute (Nalchik, former USSR) in the early 1960s. The idea was to introduce large numbers of artificial embryos (using rockets and/or artillery cannons), which compete for the limited water content in clouds and, as a result, reduce the size of the growing hailstones. As revealed by later research, the complexities of hailstorms and the details of hailstone growth turned out to be much more complex than it was assumed in the simple notions underlying the idea of beneficial competition. Hereafter, in the 1970s, Magomet Abshaev proposed a new concept of *"premature precipitation"* (Abshaev 1966, 1994), artificially induced in feeder clouds of mature hailstorms earlier than it would occur naturally; this would lead to the depletion of a cloud's liquid-water content required for hail growth. Another concept of *"trajectory lowering"* was proposed by Brant G. Foote from the National Center for Atmospheric Research in the USA, which anticipated limiting the hail growth level by the enlargement of artificial ice particles in hailstorms (Borland et al. 1977). Implementation of CS for hail-damage mitigation has evolved considerably, though modification of mature hailstorms is still controversial.

Another area of application of RE has been for extinguishing forest fires. Meteorological observations on the state of the atmosphere in forest-fire zones made by the Research Institute of Forestry (Russia) showed that powerful convective clouds with volumes of tens of cubic kilometers that do not produce precipitation often appear above forest fires. Each km^3 of clouds contains an average of 1,000 t of water, so clouds above regions of active forest fires are natural reserves of water. In the former USSR, back in the late 1960s, a method for extinguishing forest fires using artificially induced precipitation was proposed (Burtsev et al. 2018). Experimental and practical work in various regions of Siberia indicated prospects for its application.

Over the 80-year history of WM experimentation, the interest in WM has varied significantly. There was a major increase in commercial CS activities in the early 1950s. Since numerous attempts to modify weather systems did not produce verifiable positive outcomes, it became obvious that some basic questions had yet to be addressed. Consequently, intense research activities were undertaken in the universities and government agencies during the 1960s and the early 1970s (Al Mandous et al. 2006).

One major international effort toward deeper understanding of the effects of CS on cloud and precipitation development was the World Meteorological Organization (WMO)-initiated major international RE Project in Spain in the late 1970s and early 1980s (WMO 1985). Through more than 30 relevant reports, the RE Project established important scientific principles for the planning and execution of such experiments. Currently, according to the WMO Registers, there are dozens of nations operating hundreds of WM projects, particularly in arid and semi-arid regions. More than 70 countries have expressed their interest in how to use RE as part of their water resource-management strategy.

2.3 Status

The development of new equipment—such as weather radars, satellites, microwave radiometers, wind profilers, automated rain gauges, mesoscale network stations, and aircraft platforms with microphysical and air-motion measuring systems—has introduced new dimensions into WM operations and research over the last three decades. Equally important are the advances in computer systems and algorithms for cloud processes that permit higher resolution and more physically based simulations to be run in relatively short times. New field observations used in conjunction with increasingly sophisticated numerical cloud models have helped in testing various WM hypotheses. Through some of these innovative facilities, a better understanding of clouds and precipitation climatology can be achieved to test seeding hypotheses prior to the commencement of WM projects.

The complexity and variability of clouds cause certain difficulties in understanding and detecting the effects of artificially modifying clouds. The ability to influence cloud microstructures has been demonstrated in the laboratory, simulated by numerical models, and verified through physical measurements in some natural systems such as fogs, stratus, and cumulus clouds. The confidence level in being able to generate predictable results is quite high for the dissipation of supercooled fog and moderate to high for increasing snowfall from orographic clouds. However, statistical evidence for the degree of artificial modification on precipitation, hail, lightning, or winds is limited. Experiments have suggested a positive effect on individual convective cells, but conclusive evidence that such seeding can increase rainfall over large areas has yet to be established.

The expected effects of seeding are often within the range of natural variability (low signal-to-noise ratio), and our ability to predict the natural behavior is still limited. Randomization methods, augmented by physical predictors, are considered to be the most desirable for detecting cloud-seeding effects. Coupling of physical experiments with ongoing operational projects would be a productive and cost-effective approach to collect information for the clarification of questions related to WM. RE projects are generally expected to yield increases of 10-20%, however that level of success is difficult to achieve in measurements and in the simulation of precipitation.

The success of WM depends on the understanding of the related disciplines (cloud physics and dynamics, mesoscale weather forecasting, numerical modelling of cloud processes, and measuring technology). This explains why progress has been slow in establishing the validity of WM results. There is growing evidence that the basic concepts are correct and that successful implementation is feasible.

2.4 Technological Interventions

The purpose of CS is to change the microphysical processes in clouds to increase the efficiency of precipitation formation. This can be obtained by accelerating the condensation–coalescence–collision–freezing processes that promote early development of precipitation and thus harvest more of the available water from clouds.

The CS operation can be divided into six basic elements (Fig. 2.1). As a first step, suitable clouds or cloud clusters need to be identified. Cloud characteristics such as type, vertical depth of the cold and warm parts, liquid-water content, spatial dimensions, tendencies of development, etc. must be observed and evaluated to select a suitable cloud. The second step is to select proper seeding materials (SM) depending on the cloud type (warm/cold or mixed phase). Glaciogenic agents are used for clouds with high super cooled liquid-water content (SLW) in the cold part, while

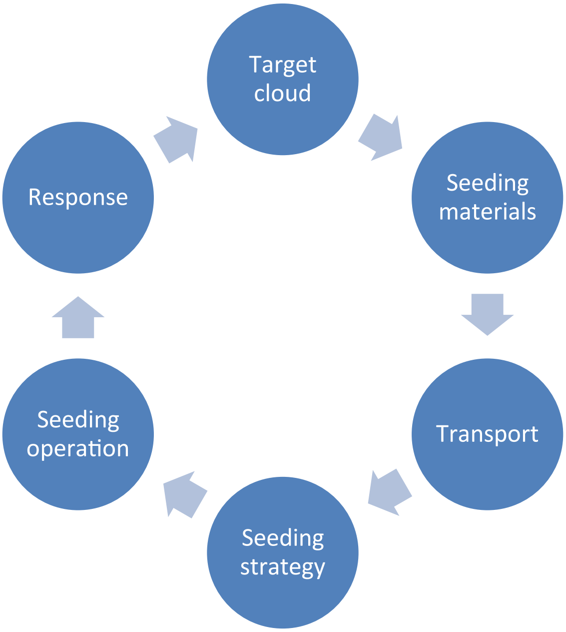

Fig. 2.1 Simplified components of cloud seeding through six basic elements

hygroscopic agents are the only option for warm clouds. An optimal delivery system should then be selected (e.g., aircraft, artillery shells, rockets, ground generators, etc.). A seeding strategy is implemented to determine the optimal location, time, and dosage of seeding, as well as its frequency, until a decision is made to stop the seeding. The next element in the chain is the seeding operation itself, and the last is the measurement of the seeding response based on the analysis of radar-satellite-ground data.

2.4.1 Seeding Materials

Most WM methods are based on the introduction of a large amount of special artificial aerosol particles into the cloud environment. According to the principle of action, such particles called seeding materials can be divided into two large classes: *glaciogenic* and *hygroscopic*. Glaciogenic seeding introduces ice-nucleating particles (INP) into the cloud to enhance the ice/mixed phase, while hygroscopic seeding introduces cloud-condensation nuclei (CCN) to enhance the formation of larger drops and activate the coalescence process. Depending on the type of cloud and the purpose of the WM, one or the other is selected.

For *glaciogenic seeding*, AgI and dry ice are still the most widely used SM. Both materials enhance ice-crystal concentrations in clouds by either nucleating new crystals or by freezing cloud droplets. AgI nucleates ice particles at temperatures below −2 °C to a minimum of −10 °C. Based on past experiments, two seeding concepts have been proposed, namely, the "static" and "dynamic" (Braham 1986). While the first attempts to increase precipitation embryos, the latter attempts to increase the buoyancy in the cloud through the release of latent heat due to the freezing of supercooled liquid drops (National Research Council 2003).

Silver iodide can be dispersed either by pyrotechnic flares from generators at the surface or in the air. For the ejectable flare, ignition occurs as it leaves the aircraft. Pyrotechnic flares typically produce 10–100 g of active seeding agents per minute of burn, whereas aerial acetone generators produce 2–3 g of active seeding agent per minute. In anti-hail rockets, AgI is sublimated in a special chamber in the head of the rocket or in its engine combustor (Abshaev et al. 2014).

The earliest experiments on CS used pellets of dry ice dropped from aircrafts (Dennis 1980). Dry ice is dispensed through openings located in the floor of baggage compartments of CS aircraft. Dispensers disperse pelletized (0.6–2.5 cm) or small particles of dry ice. Dry-ice pellets have a surface temperature of around −78 °C, and so they freeze any cloud droplets in their paths, and they also activate cloud-condensation nuclei to form droplets that freeze through homogeneous nucleation.

Hygroscopic seeding is potentially applicable to all clouds that have a liquid region. Typically, hygroscopic seeding particles are larger (a few microns) and more hygroscopic than the natural aerosol particles. The resulting droplets grow to larger than normal sizes through condensation, and then they rapidly grow further through collisions with other droplets (Cooper et al. 1997), initiating the rain process within the convective cell. There are two main concepts under consideration regarding hygroscopic seeding: the competition effect and the tail effect (Segal et al. 2007). The tail effect envisages the droplets' spectrum broadening by large seed particles, while competition is based on more efficient droplet formation compared to natural CCN.

Hygroscopic seeding in convective clouds is carried out with the help of aircraft-based flares through a burning process or the dispersion of prepared micro-powders of either pulverized salt; alternatively, or pyrotechnic flares are used. The principle of hygroscopic flare seeding is based on the flares producing effective CCN particles in larger sizes (large or giant nuclei) than occur in the natural environment (Bruintjes et al. 2012). Hygroscopic flares contain sodium chloride or calcium chloride, which produce small salt particles in the size range of 0.1–10 μm in diameter.

Cooper et al. (1997) found that an optimum particle size of 1 μm is required to form drizzle drops and to enhance collision-coalescence processes. The optimum size of soluble particles was found to be 1–5 μm (Segal et al. 2004; Rosenfeld et al. 2010). It is also important to have information on the particle-size distribution of naturally present aerosols, recognizing that, if the procedure occurs close to a coastline, it can be dominated by the already large sea-salt aerosols.

Drofa et al. (2013) studied the effect of seeding of a cloudy environment with salt powder in a large cloud chamber (3,200 m^3) in conditions corresponding to the formation of convective clouds and observed that the introduction of salt powder before a cloud is formed in the chamber results in the formation of a "tail" of additional large drops. In this case, seeding with the salt powder also leads to an increase in size of the entire population of cloud drops and to a decrease of their total concentration as compared to a cloud that is formed of background aerosols, showing that a salt powder milled to a size of several μm is more effective in initiating warm rain than hygroscopic flares. While the chamber experiments and numerical simulations provide some evidence of the effects of salt-powder seeding, their validation in the real atmosphere is still needed. Belyaeva et al. (2013) showed with numerical simulations that the use of polydispersed salt powders has an advantage over hygroscopic agents from pyrotechnic flares and that precipitation could be induced from warm convective clouds of moderate thickness that do not precipitate naturally. Zhekamukhov and Abshaev (2009a and b) showed that anti-hail rockets equipped with hygroscopic micro-powders could be effectively used for seeding the cores of developed cumulus-congestus clouds for the purpose of RE. The optimum suggested size of NaCl crystals is 7.5–10 μm because these "salty" droplets can rapidly grow to raindrops size through condensation–coalescence mechanisms.

In recent years, new formulations of SM are being developed for release from pyrotechnic flares (National Research Council 2003). These materials require less AgI than previous formulations, and they are much more active in ice nucleation at temperatures colder than about −5 °C. Considerable work to improve the efficiency of SM is being carried out by numerous groups using complex chemical compositions, nano-technologies, various types of cloud chambers, and full-size testing stands of seeding devices (Drofa et al. 2013; Liang et al. 2019; Tai et al. 2017).

2.4.2 *Transport and Dispersion*

Seeding material can be dispersed into clouds and their surroundings by aircraft, artillery shells, small-sized rockets, high-altitude fireworks, unmanned aircraft, balloons, and ground-based generators (Figs. 2.2 and 2.3).

Any CS program should first determine the transport, dispersion, and dilution of SM in the clouds to supply the right quantities at the right time to the right place in the clouds. The temperature range, cloud type, delivery mechanism, and seeding targets are all crucial factors to be considered. Seeding materials act locally and dissipate with time due to thermodynamics, transport by advection–convection forces, and turbulent mixing.

There is no universally ideal delivery system, and each method has advantages and disadvantages. Aircrafts are used to disperse SM from the sub cloud and cloud-top levels and directly in super cooled regions of winter orographic clouds. However, penetrations of convective clouds are rarely practiced for safety reasons, as well as nocturnal flights, because of the limited visual contact. Due to the risks associated with carrying flammable liquids on aircraft, pyrotechnic flares have been developed for aircraft-based seeding (Dennis 1980). For seeding from cloud base or top, a certain period of time is required (5–10 min) until the SM reaches the level of maximum water content. Aircrafts enable coverage of large areas and the measurement of meteorological characteristics along the flight path. Hygroscopic seeding is mainly

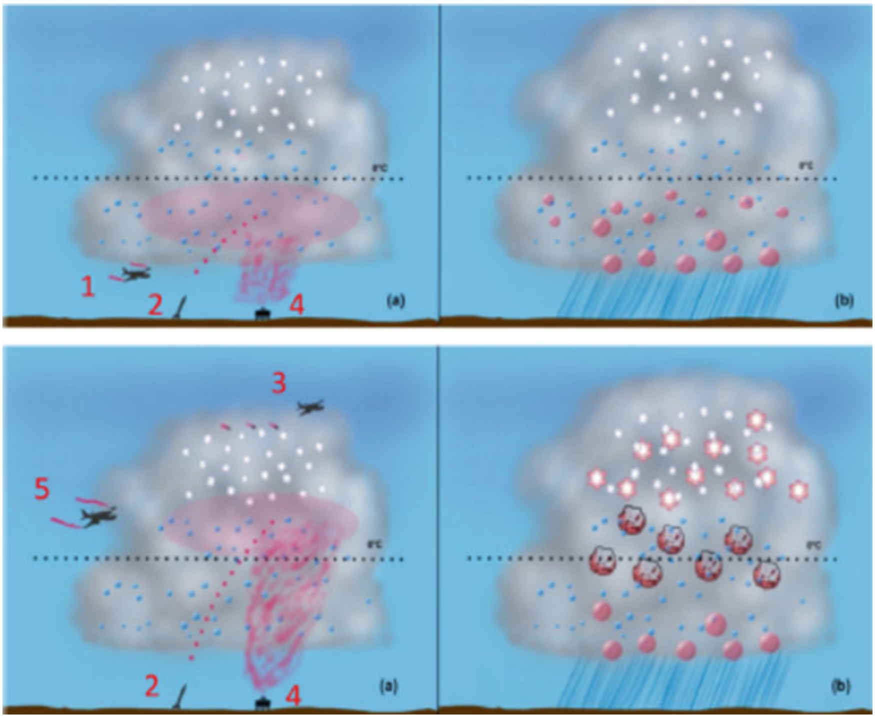

Fig. 2.2 Rain enhancement through could seeding using aviation, rocket, or ground-based generators of nuclei for crystallization or condensation: **a** refers to seeding options and **b** indicates the intended outcome of the seeding. The seeding options include: (1) cloud-base aircraft; (2) rockets; (3) cloud-top aircraft; (4) ground generators; and (5) direct cloud penetration by aircraft (Flossmann et al. 2019; © American Meteorological Society. Used with permission)

dispensed from aircraft at the cloud base through flares or salt powders, while dry ice and ejectable flares are used for cloud-top applications.

Rockets and artillery shells are used for direct and almost simultaneous seeding of the required cloud part in the required dosage in 24/7 mode irrespective of cloud conditions (turbulence, lightning activity, heavy solid/liquid precipitation). One rocket site serves a ground circle of 100–300 km^2. But this requires well-developed infrastructure and logistics on the ground maintained by personnel. State-of-the-art progress now makes possible robotizing ground sites using automated rocket launchers without personnel (Abshaev et al. 2011a). Launching is prohibited when ground-level winds exceed 20–25 m/s. Rocket launch permission should first be obtained from the regional aviation authorities.

Ground-based generators mainly apply AgI in pyrotechnic flares or in acetone. The main problem here is the large temporal and spatial distance from the aerosol generator to the cloud. Only a fraction of the SM, if at all, reaches the cloud base when airflows are favorable. Deactivation of SM due to the impact of high humidity,

Fig. 2.3 Technical systems for delivering seeding materials into clouds and their environments: **a** airborne pyroflares; **b** small-sized anti-hail rocket “Alazan-6” and automated anti-hail launcher “ELIA-2”; **c** liquid acetone-based ground generator. *Sources* **a** National Center of Meteorology of the United Arab Emirates; **b** Magomet Abshaev; **c** Viktor Korneev; all used with permission

ambient aerosol and ultraviolet is another challenge when employing this method (Shilin et al. 2015).

A tracer (chaff and/or SF6) can be used as a tag for a seeded region to understand the dispersion and transport of the SM. Chaffs can be monitored by radar (Reinking and Martne 1995), while detection of the SF6 is done by aircraft (Rosenfeld et al. 2010). SF6 tracers have been used by Rosenfeld et al. (2010) for identifying seeding signature in convective clouds over Texas in the USA.

Studies of the transport and dispersion of SM in convective clouds were conducted in Moldova for 20 consecutive summers. Special tracers based on deuterium $210P_o$ and D_2O (Dinevich and Shalaveyus 2010) were introduced into the clouds by rockets and aircrafts. A dual-wavelength radar MRL-5 was used to measure cloud characteristics, while rain gauges and laboratory equipment were used to detect tracers in precipitation on the ground.

2.4.3 Seeding Strategies

The selection of a seeding strategy predominantly depends on the type and characteristics of the clouds, SM, and delivery methods. Hygroscopic seeding involves seeding summer time convective clouds below the cloud base with pyrotechnic flares that produce salt particles (~0.5 μm) that are larger than naturally available CCN. The particles are supposed to activate at lower supersaturations and condense water more readily, as well as limit the total number of droplets activated. The degree of concentration of the background aerosol population needs to be considered (Semeniuk et al. 2014). Cloud droplets should nucleate preferentially on the seeding particles, and this inhibits smaller natural CCN from activation, resulting in a broader-than-natural droplet spectrum near the cloud base, triggering collision coalescence within 15 min (Cooper et al. 1997), and initiating the rain process earlier within the 30-min lifetime of a typical cumulus cloud. This is expected to increase the potential for precipitation to develop earlier and more efficiently in the lifetime of the cloud.

For glaciogenic seeding, introducing INP close to cloud base will yield an effect like hygroscopic seeding because the AgI particles are large enough (~0.1 μm; Dessens et al. 2016) to serve also as CCN. Reaching higher altitudes, the INP freeze the SLW drops and trigger precipitation via the formation of graupel particles. Depending on the height of the freezing level, the particles will melt before reaching the ground. Because the direct penetration of the SLW is dangerous for aircraft, the release of SM is realized from sub cloud or cloud-top levels for the majority of aircraft-based seedings of convective clouds. Applying this seeding strategy, one must account for the time required for the SM to attain the necessary levels of SLW in the cloud, which can take several minutes. Artillery shells (Zhekamukhov and Abshaev 2012) and anti-hail rockets (Abshaev et al. 2014) are widely used to deliver glaciogenic SM directly to a specific altitude for the SLW of convective clouds in the required dosage. Dispersed from sub-cloud and cloud-top levels or directly into regions of SLW, deposition of water vapor onto the introduced INP is supposed to be the main mechanism for the growth of ice particles.

Given the variability of operating conditions, it is important to ensure that seeding generators produce a steady flow of SM and that the particle-size distribution and number and mass concentrations of the SM are documented (Huggins et al. 2008). These precautions are needed to ensure that any seeding effects can be related accurately to the source characteristics. It is also vital to ensure that the plumes from generators are dispersed into regions of the cloud where they can interact with available SLW.

The targeting and dispersion of SM remains an important issue in seeding experiments and needs to be validated by observations and numerical model simulations (Xue et al. 2013a; French et al. 2018; Abshaev et al. 2004, 2011b). Routine targeting is achieved using a suitable model, which can vary from rather simple dispersion-microphysical models to full three-dimensional numerical models. A CS parameterization in the weather research and forecasting model used by Xue et al. (2013b) suggests that the effects of aircraft-based and ground-based seedings are different. For aircraft-based seeding, where the SM is dispersed directly into regions of SLW, deposition of water vapor onto the introduced ice nuclei is the main mechanism for the growth of ice particles. However, for ground-based seeding, where the SM must be mixed vertically into the SLW region, the dominant effect is probably from AgI acting as CCN when temperatures are warmer and subsequent immersion freezing because the introduced ice nuclei are incorporated into the SLW droplets before freezing occurs. Three-dimensional modelling by Xue et al. (2013b) confirms that in general direct (by aircraft, rockets, and artillery shells) and near cloud (by aircraft) methods of CS are more efficient.

Recent advances in technology provide a new dimension to the targeting and evaluation of CS experiments. Radar polarimetric parameters can be used to identify the zones of hydrometeor classes that may be targeted with more precision and may help with the selection of the areas for seeding. High-quality real-time radar observations illustrating various types of hydrometers and other analytical products from dual polarization radar networks in the world seem to have a large potential for the targeting and evaluation of CS experiments.

The new generation of geostationary satellites enables tracking of clouds at higher resolutions, and so cloud tops and other spatial structures will be discernible. Information on cloud types and microphysics during potential seeding days, especially the relationship between cloud-top temperature and effective radius (Rosenfeld and Lensky 1998), together with estimates of vertical velocity and CCN information, can be derived. This information, together with sophisticated numerical modelling, gives guidance for seeding decisions.

Optimal seeding conditions may be determined based on guidance from high-resolution weather-forecast radar visualization using improved analysis tools (such as TITAN, ASU-MRL, etc.) that can handle the selection of variable target/control areas or individual radar cells (Woodley et al. 2003; Abshaev et al. 2010).

2.4.4 Seeding Operation

Cloud Seeding is usually done at the cloud base and top and by direct introduction of the reagent at the desired height inside the cloud. The reagent delivery is carried out by light and medium-sized aircrafts, small-sized rockets, artillery shells, or ground generators (Fig. 2.2).

2.4.5 Response and Impacts of Cloud Seeding

Quantifying the impact of CS has been a longstanding challenge and has been attempted via many methods (Rauber et al. 2019). The main problem is to detect the signal caused by CS against the background of natural variability in the development of cloud processes (noise). For this purpose, various statistical methods have often been used (Woodley et al. 2003; Brier et al. 1973; Yao 2006; Guo 2015; Manton et al. 2011; Breed et al. 2014; Rasmussen et al. 2018; and others). However, relatively small sample sizes have limited the conclusiveness of these statistical approaches (Rauber et al. 2019).

The seeding response of clouds is often understood as a change in their micro- and macro-physical parameters (Abshaev et al. 2014, 2009; Al Mandous et al. 2006; Bruintjes 1999; Flossmann et al. 2019; Koloskov et al. 2011), and attempts have been made to measure these parameters to physically detect the response. Specific parameters expected to be impacted by CS vary depending on the type and purpose of seeding, but include the cloud's liquid and ice-water content, the vertical extent of the cloud, the volume of the cloud, the intensity and amount of precipitation, the area covered by precipitation, the precipitation path, radar reflectivity, and other parameters measured in situ (Fig. 2.4), remote-sensing (weather radars, microwave satellite and ground radiometers, lidars, etc.) and ground-based instruments (rain gauges, river runoff, snow depth, etc.). For example, for the purpose of detecting physical efficacy of cloud seeding for hail mitigation, Abshaev et al. (2003) suggest applying map of hail kinetic energy (E, J/m^2) integrated over relatively long periods in terms of month and years calculated based on radar data (Fig. 2.5). Comparison of integrated E multiplied by square of protected and adjacent (control) areas can be used for estimation of physical effect of HS.

A novel approach is to use numerical cloud models to augment statistical and experimental cloud-seeding programs (Geresdi et al. 2017; Segal et al. 2004; Xue et al. 2013a; Zhekamukhov and Abshaev 2009a). Recent improvements in the sophistication of numerical models, aided by the advances in supercomputing, make possible very high-resolution three-dimensional simulations that have the capability to simulate cloud seeding in a physically meaningful manner and account for model uncertainty using ensemble modeling methods (Rasmussen et al. 2018). Newly obtained observations of the seeding impact in winter orographic clouds (French et al. 2018, Tessendorf et al. 2019) have provided unprecedented datasets

Fig. 2.4 Highly equipped middle-sized research aircraft “ROSHYDROMET YAK-42D” of the Russian Hydrometeorological Service for measurement of atmospheric and cloud characteristics and cloud seeding, using various types of seeding materials: **a** external view; **b** sensors for aerosol, cloud droplets, and ice crystals spectrum, temperature, humidity, water content. *Source* Viktor Petrov; used with permission

to thoroughly quantify the physical response of precipitation production to seeding (Friedrich et al. 2020; Fig. 2.6) and to validate numerical models (Rauber et al. 2019).

Recently, French et al. (2018) carried out complex measurements of orographic clouds seeded from aircraft using ground-based X-band radars, an airborne W-band cloud radar, and instrumented aircraft for employing in-situ cloud-physics probes. They found the strongest evidence for the initiation and growth of ice crystals as a result of glaciogenic seeding with AgI, leading to precipitation (snow) on a mountain surface within a specific target region. These observations, in two separate cases, showed the initial appearance of cloud-seeding signatures within 30 min following the release of AgI in the cloud. Seeding lines were tracked, and the evolution of ice crystals to precipitating snow was documented (Fig. 2.7). These comprehensive

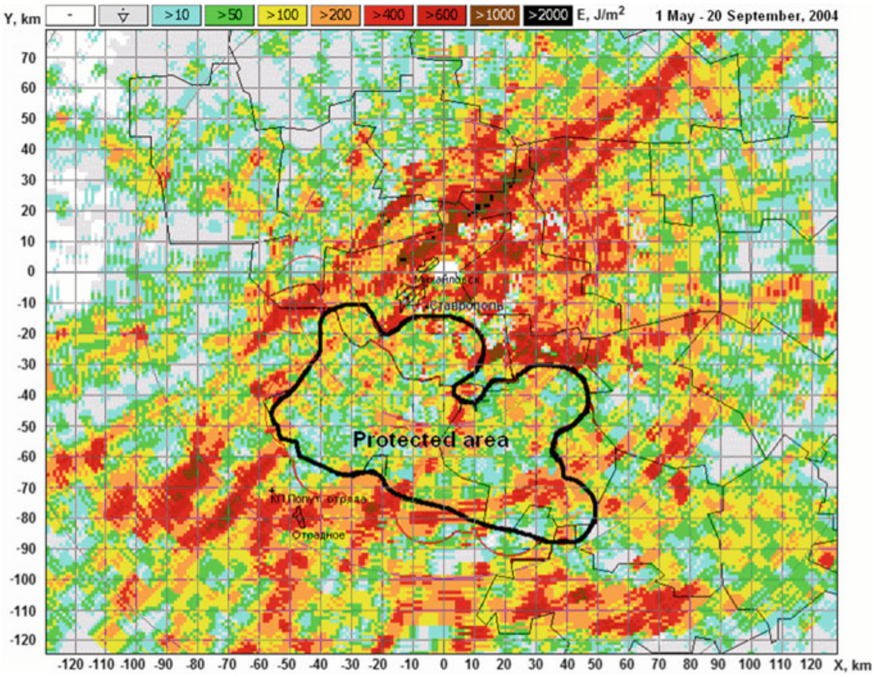

Fig. 2.5 Example of radar-measured kinetic energy (E, J/m^2) of hail in the Stavropol district of Russia, collected from 1 May to 20 September 2004. The black contour denotes the area where hail clouds were seeded (*Source* Abshaev et al. 2006)

observations provide unambiguous evidence that glaciogenic seeding of a supercooled liquid cloud can enhance natural precipitation growth in a seeded cloud, leading to precipitation that would otherwise not fall within the targeted region.

2.5 Could-Seeding Conditions

It is important to specify the environmental conditions that must be satisfied before the seeding is commenced. For example, these seedability criteria need to ensure that there is SLW that can be converted into ice crystals by the glaciogenic SM in the cloud. In turn, the ice crystals can grow and ultimately fall into the target area. To ensure that the SM properly interacts with the SLW, there are also conditions on the dispersion and targeting of the SM, with the specific conditions dependent upon the seeding strategy. The targeting conditions require a range of wind speeds and directions to allow for the mixing of SM from ground-based generators to a level where the SM activates ice nuclei. Manton et al. (2011) found that seeding from ground-based generators was not effective at low wind speeds.

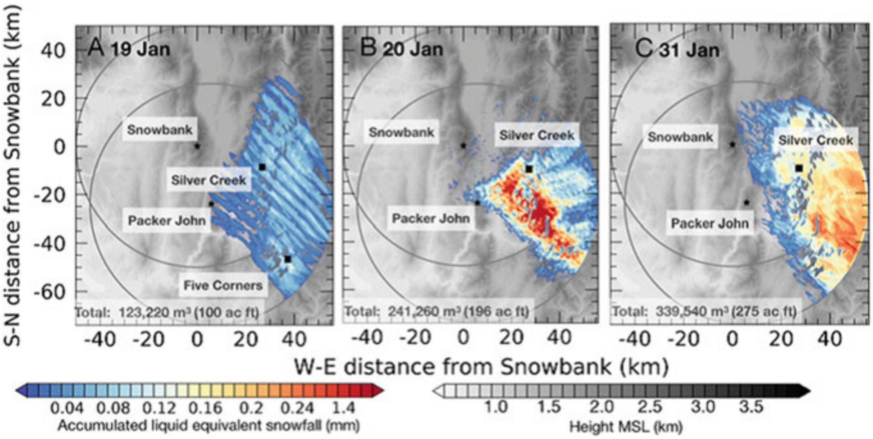

Fig. 2.6 Distribution of accumulated liquid-equivalent snowfall (S) attributed to parallel cloud seeding lines over the observational period between **a** 1705 and 1806 UTC on 19 January; **b** 0042 and 0315 UTC on 20 January; and **c** 2117 and 2151 UTC on 31 January 2017, using the best-match Ze–S relationship for that day. Data are shown on a 100 × 100 m grid. Total accumulations over the entire domain and observational period are highlighted (*Source* Friedrich et al. (2020), used with permission of PNAS)

Also, the aerosol particle population of the ambient air needs to correspond to the selected seeding method, potentially excluding certain population scenarios for mixed-phase clouds. The dispersion of SM to interact with available SLW is the first step to ensuring that any enhanced precipitation falls into the target area. SM such as AgI leads to ice nucleation at temperatures colder than about −5 °C, and so it is usual to require cloud-top temperatures to be less than about −8 °C (Breed et al. 2014). By considering the ratio of seeded to unseeded precipitation in the target area, it is often implicitly assumed that the seeding impact is multiplicative. This assumption implies that there needs to be some natural precipitation during seeding that is enhanced by seeding. Manton et al. (2017) demonstrated that there was a negligible impact of seeding when the natural precipitation was low, and so it was preferable that some precipitation was falling at the time of seeding commencement. Related to this condition is the need for a forecast of seedable conditions to persist over the duration of seeding. Such forecasts are usually developed through analysis of numerical-model results.

2.6 Economics

The economic benefits of RE arise from the value of the increased water reaching the ground. That water will either directly feed agricultural crops or more likely lead to increased runoff into regional hydrological systems. However, the major challenge

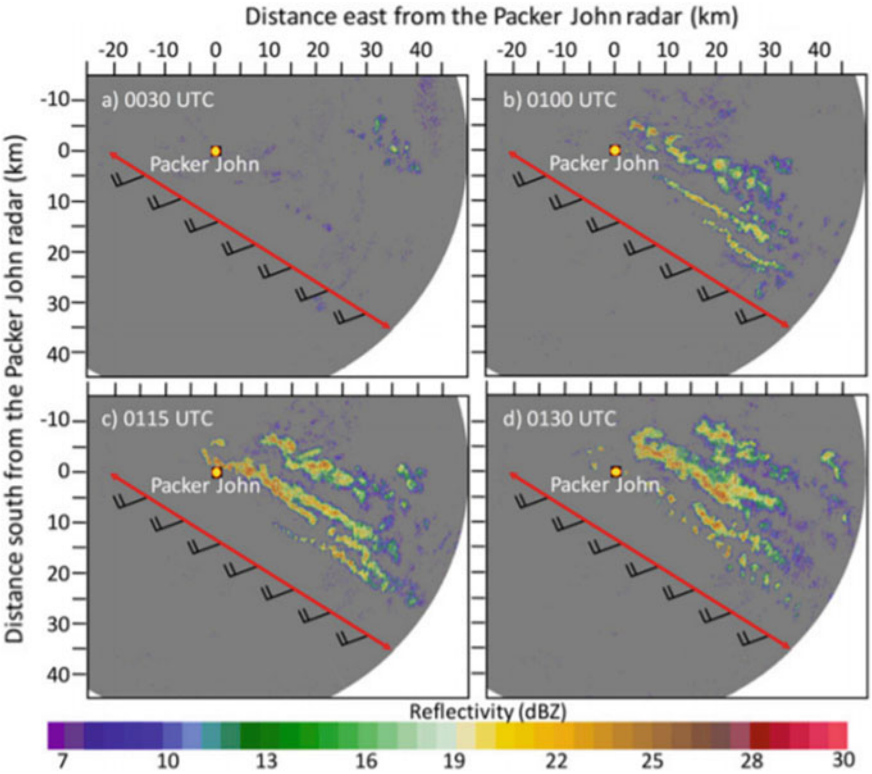

Fig. 2.7 Radar reflectivity from the ground-based Doppler radar located at Packer John mountaintop for four time periods more than 60 min after beginning seeding: **a** 0030, **b** 0100, **c** 0115, and **d** 0130 UTC. The scans were conducted at a 2° elevation angle and, therefore, show the reflectivity just above ground level close to the radar to roughly 1.7 km above ground level at 50-km range. The red line indicates the track of the seeding aircraft, which was repeated eight times. Wind barbs plotted on the aircraft track illustrate mean wind direction and speed (in m per sec) at flight level. Each barb is 10 m s^{-1}. (*Source* French et al. (2018), used with permission from PNAS)

is that the physical processes extend across an extremely large range of spatial and temporal scales. The spatial scales range from submicron to synoptic scale, while the temporal scales can range from microseconds to several hours or longer. One of the often-neglected issues in RE is the scaling up from small to larger scales. This relates to the consideration, explanation, and provision of proof through each link in the chain of events, from the seeding intervention to more precipitation on the ground, in such a way that the result has an acceptable impact with a desirable benefit–cost ratio. This challenge should be viewed in tandem with all the practical and logistical considerations when scaling up from single-cloud experiments to area-wide impacts. The recent observations of French et al. (2018) provide substantial evidence of this chain of events for wintertime orographic seeding. This issue is especially critical and difficult when dealing with convective clouds. Some of these issues were studied by Terblanche et al. (2000) during a semi-operational RE experiment in South Africa. The authors attempted to link the apparent positive storm-scale seeding effect to an observed larger-scale rainfall anomaly observed in the rainfall records in the area of seeding. However, simple calculations proved that there was a "two orders of magnitude challenge" between what could have been realistically expected from the seeding interventions on a storm scale and what was observed in the area-wide rainfall records for the rainfall season. They concluded that the interventions and observations were probably unrelated. In a similar scenario, Terblanche et al. (2005) attempted to calculate the cost–benefit ratio of additional rainfall in a continuation of semi-operational experiments in South Africa. For this purpose, he studied the storm climatology to estimate how many storms will have to be treated in a rainfall season to have the desired area effect if the storm effect they observed could be used as the basis for calculation. From these studies, it became evident that rainfall enhancement could be more favorable than other options to address water stress in South Africa, but there could be several logistical challenges in treating the number of storms required, even though there appear to be sufficient candidate storms for treatment. As most storms develop in a short period of time in the afternoon, the authors concluded that new, more efficient ways to deliver SM (other than standard aircraft) will have to become a priority for the future. Even for winter orographic CS, careful calculation is needed to ensure that the benefit outweighs the cost.

For both the Snowy Rain Enhancement Research Project (Manton et al. 2011) in Australia and the Wyoming Weather Modification Pilot Project (Breed et al. 2014) in the USA, the fractional increase in precipitation for seedable events is on the order of 15%. But seedable events generally make up only a fraction of the overall annual or seasonal precipitation. Moreover, the transformation of precipitation on the ground into hydrological streamflow incurs losses from evaporation and recharging of groundwater, as well as delays, as the water passes through the complex hydrological system.

The relatively small precipitation signal and the complexity of the hydrological system mean that it is very unlikely that the impact of CS could be detected directly in measurements of streamflow or dam volume. Detailed rainfall–runoff modelling is needed to estimate the actual increase in annual streamflows due to CS. On the other hand, the increasing scarcity of potable water around the world means that the potential benefits of CS will continue to increase, while the costs should remain constant or decrease due to technological and scientific advances.

It is not uncommon for communities to seek relief from drought through CS activities. Indeed, Yoshida et al. (2009) found that seeding in Japan may be effective for drought relief. On the other hand, in many countries especially those affected by the El Nino-Southern Oscillation phenomenon (Nicholls and Wong 1990), the variability of precipitation is so high that periods of drought are associated with an essential absence of clouds suitable for seeding. Thus, the cost–benefit analysis for a project needs to account for the prevailing climatic conditions. On the other hand, despite the lack of evidence of area-wide and seasonal-scale impacts, seeding is often carried out on convective clouds based on the potential for a significant benefit at a relatively low cost (Bruintjes 1999). Such strategies are viewed as a component of an overall approach to risk management of water resources, bearing in mind the substantial scientific uncertainties.

2.7 Redistribution and "Negative Enhancement" of Precipitation

The areas affected by CS remain an open question, especially with regard to convective systems. Related uncertainties pertain to the issue of "extra-area" effects, that is, whether seeding can affect the weather beyond the targeted temporal or spatial range. The persistent effects of CS claimed by Bigg (1995) should be carefully assessed, as should the statistical results from experiments in Thailand (Woodley et al. 2003) and Israel (Brier et al. 1973), which claimed effects beyond a few hours.

Some professionals argue that increasing precipitation in one region could reduce precipitation downwind (by "stealing" the atmospheric water vapor); for example, recent modelling studies by Geresdi et al. (2017) suggest that in some circumstances there may be a decrease in precipitation on the leeside of a mountain, even when there is an overall increase over the whole domain. On the other hand, analysis by Long (2001) suggests that enhanced downwind precipitation may be promoted by the transport of ice nuclei and ice crystals or by the dynamic invigoration of clouds through the release of latent heat. Overall, further quantitative studies are needed to resolve these issues, bearing in mind the uncertainties in assessing the impacts of seeding in a designated area.

Givati and Rosenfeld (2004) suggested that urban air pollution in California and Israel may reduce annual rainfall by about 15–25%. According to Khain et al. (2005), small CCN may produce small droplets, which have small collision efficiency, thereby reducing precipitation from deep convective clouds. Introducing superfine hygroscopic SM into the clouds would then initiate the formation of small droplets that compete with existing cloud droplets in the water-vapor absorption process within the cloud. This method may prevent the development of precipitation in some cases. On the other hand, introducing giant hygroscopic SM into clouds can increase the collision efficiency of droplets and lead to the rapid development of rain. This mechanism can be applied to developing upwind clouds with the potential to produce rain over a substantial target area. This "jumping process mechanism" can then reduce the potential of the cloud to develop rain over a target area.

During the last 30 years, considerable work has been done in Russia on precipitation redistribution above megalopolises and neighboring areas to prevent rain occurrences during important local events. More than 80 projects have been completed on national holidays (Koloskov et al. 2011), with various (cold and warm) types of clouds (stratus and convective) being seeded by 6–12 aircrafts dispersing AgI, liquid nitrogen, solid carbonic acid, coarse-dispersion powders, and hygroscopic particles. Four different methods are commonly used, depending on the synoptic situation: (a) dispersion of stratiform clouds; (b) destruction of convective clouds or reduction of the intensity of shower rains and thunderstorms; (c) premature initiation of precipitation from clouds on the upwind side of the target area to create a "precipitation shadow" over the given site; (d) reduction of rainfall intensity over the target area by intensive seeding of the rain-producing clouds moving toward it; this is aimed at weakening the mechanism of precipitation formation through "overseeding", i.e., by creating excessive concentrations of ice crystals. However, further quantitative substantiation of precipitation redistribution is needed, especially for convective rainfall.

Debates about the effects of seeding beyond the target area point to the fact that WM can be viewed as more than just a means to increase local precipitation. Rather, it can be viewed as a means to alter natural hydrological cycles by increasing the number of times that atmospheric water is recycled at the Earth's surface. As more is learned about the global water balance, and as new tools enable cloud scientists to better understand clouds and their response to seeding, the question of extended area effects will likely become better defined and understood. All these effects will have to be considered against the background of climate change and the associated changes in precipitation in time and space globally.

2.8 Environmental Issues

By design, precipitation enhancement aims to alter the natural environment, and so there is a potential for undesirable changes to the environment. Dennis (1980) gave a critical analysis of the risks associated with CS, including toxicological, ecological, sociological, and legal challenges. He noted an absence of evidence of environmental hazards, and this conclusion has been confirmed over the ensuing decades. Lincoln-Smith et al. (2011) studied the potential risk of the SM (particularly silver and indium) to the overall environment of the Snowy Mountains in Australia. Observations at the generator sites showed that levels of seeding chemicals were well below any trigger levels for health concerns and there was no indication of accumulated impacts over a five-year period. Abshaev et al. (2014) analyzed the results of measurements of AgI and PbI_2 in air, soil, water reservoirs, and precipitation in regions with long-term (more than 40 years) implementation of artillery and rocket HS technology in specific areas (Northern Caucasus, Moldova, and Georgia), and found that the maximum concentration of these hazardous pollutants is several orders below the maximum allowable concentration specified by the World Health Organization. Moreover, Korneev et al. (2017) showed that the utilization of AgI in aircraft seeding in Russian investigations did not lead to measurable increases in the level of these chemicals due to natural and anthropogenic sources. They suggested that seeding has extremely low impacts on the environment, and they did not observe any extra-area effects. Therefore, studies conducted in Russia suggest that direct delivery of SM into clouds should cause no ecological concern even after decades of implementation. On the other hand, Fajardo et al. (2016) used laboratory studies to suggest that some biota could be adversely affected if "large amounts of SM accumulated in the environment".

2.9 Planning Rain Enhancement Projects

Given the state of knowledge about WM, it is important to consider how to plan activities so that they might gain both social and scientific acceptance. The preference of the scientific approach for WM experiments is to carry out well-designed long-term experiments involving proper physical and statistical controls and cloud-physics measurements prior to and during the operations. At each stage in the planning, execution, and evaluation of a WM experiment, it is necessary to consider meteorological and cloud-physics aspects, statistical approaches, and economic, social, and environmental aspects.

Economic analyses have shown that successful RE operations could have real economic benefit, but the impacts of operations have still not been properly quantified. Despite some of the uncertainties of WM, RE remains a potential option and should be viewed as a part of an integrated water-resource management strategy. Each project should be treated as a possible tool among others for water-resource management and should be considered as a scientific project with the inclusion of these four phases: (a) feasibility study using the climatology of clouds and precipitation in the process of site selection; (b) design of the experiment as a function of this climatology and the present knowledge of cloud physics and WM; (c) implementation of an experiment with randomization, using extensive physical measurements and statistical controls; and (d) objective and independent evaluation of the results. Government decision-makers and funding agencies should be aware that such projects need considerable funding and well-trained personnel, as well as time to obtain conclusive results.

It is necessary to consider systematically all aspects of the set-up and proper conduction of the project, consistent with a desirable location, climatology, season, SM, delivery criteria, etc. The results of several "rain-making" projects have been inconclusive because of the lack of sound scientific planning, operation, and evaluation.

The pre-eminent need for a WM project to be planned free of non-scientific influences is very important and must be observed in the procedure for selecting the location and the season for conducting the project. Detailed feasibility studies of meteorological, climatological, hydrological, social, and environmental considerations, including the availability of logistical support are the prerequisites for the selection of an appropriate site and season to maximize the chances of achieving the objectives of RE. The RE site should be in a relatively homogeneous area for two reasons: to minimize errors in estimates of mean precipitation in the target and control areas, and to decrease the natural spatial rainfall variability, which is very important for the assessment of the results. It should be acceptable to have at least one control area with characteristics like those of the target area.

The basic measurements to evaluate and support a seeding hypothesis should be vigorously carried out. Operations should include measurements of physical response variables and should be randomized when possible to allow for an independent evaluation. Finally, attention should be given to the participants' education and training in cloud physics and associated sciences, which should be an essential component of any RE project. The RE may be economically viable and may contribute to alleviating the adverse effects of severe water shortages, but this is still to be demonstrated to the national water managers and policymakers.

2.10 Conclusions

From numerous reports, there is probabilistic evidence that RE can work with reasonable cost–benefit ratios. However, many components of RE processes must be clarified and proven. Experience in applying CS in numerous countries has shown that precipitation can be increased, ranging from essentially zero to more than 15% of the annual norm, depending on the available cloud resources, reagents, and delivery methods. Higher values tend to be associated with direct delivery of SM to the clouds utilizing aircrafts and rockets. However, the reasons for the large variation in impacts are not well understood, and estimates of impacts are sensitive to the estimation of the natural precipitation in the target area.

The current challenge is to provide a credible scientific footing for the planning of WM experiments. To be successful, any WM project should combine the efforts of funding administrators, scientists planning and working as seeding operators, and the scientific committee that assesses the scientific integrity of the project and/or evaluators.

Focusing on better understanding of the aerosol–cloud interactions (natural, anthropogenic, and seeded aerosols) and cloud microphysical and dynamical processes will bring progress also in solving problems related to the role of clouds in precipitation forecasting and climate change. Advances in cloud physics could clarify the human influence on the environment (e.g., brown-cloud, precipitation change issues), and they are not only beneficial to the field of WM but also to weather forecasting and climate issues.

It is important to emphasize that CS technology is not a "cure" for droughts. The technology requires suitable clouds for the success of a program. Unfortunately, when a drought is in progress, these types of clouds are often not available.

Well-conducted RE programs should have a systematic approach covering a wide range of factors, among which are:

- continuously evolving understanding of cloud and precipitation processes emerging from ongoing studies;
- adequate seeding hypotheses, subjecting refined seeding techniques to rigorous field testing with numerical modeling, where appropriate;
- sophisticated measuring instruments (radars, rain gauges, satellite data);
- proper SM and their cloud delivery devices;
- proven methods for assessing physical and economic efficacy, and
- regular personnel training.

Without stable, long-term support, relevant expertise, as well as a sound and systematic scientific approach, such programs will not succeed. The sustained documentation, experimentation of emerging technologies, better reagents and dispersal methodologies, and more accurate forecasting facilities to support decision making for the RE are the key factors.

Scientific understanding of cloud processes continues to increase around the world through the sharing of data and knowledge. The design, implementation, and evaluation of a catchment-scale RE experiment require a major investment of funds and resources. The sharing of the data and results of these experiments through publication in the international scientific literature provides the feedback that will help resolve the remaining uncertainties associated with CS science.

The WM has seen more than 70 years of development from Schaefer's use of dry ice pellets to produce holes in supercooled stratus by snow-out, to the present-day use of digitized radar networks and sophisticated seeding methods showing success in the RE and HS when scientific designs are applied, and proper cloud conditions exist. In the long run, the future of science-based weather modification is real. There is a growing evidence that the basic concepts are correct and that successful implementation is feasible.

The achievements are the product of international collaboration between hundreds of enthusiastic scientists working in the field. An example is to the thorough planning of the WMO Rain Enhancement Project (REP) in Spain which produced more than 30 reports on various aspects of rain enhancement. The facilitating role of the already ten quadrennial WMO Scientific Conferences on WM for the exchange of information and establishment of collaborative studies must be noted. The Indian Government has conducted a detailed science experiment named CAIPEEX to cater to the scientific evaluation of cloud seeding by both statistical and physical means. Two key national cloud-seeding projects are being carrying out in China (Yao 2006; Guo 2015), one consists of the orographic cloud-seeding experiment in six provinces of Northwest China, and the other is the Chinese Randomized Precipitation Enhancement Experiment (CRPEEX) (2014–the present) in four provinces. The experiences and results from these key projects guide and support local operational cloud-seeding activities in China. In recent years, the UAE has made an additional contribution to the scientific and practical development of rainfall-enhancement technology through the UAE Research Program for Rain Enhancement Science (Al Mazroui et al. 2017). Under the UAE's National Center of Meteorology, the program has brought together a cohort of leading scientists and institutions from around the world to untangle the complexities of the natural rainfall process and augment rainfall amounts (http://www.uaerep.ae/). A total of nine three-year distinct research projects have been funded, leveraging multiple disciplines, including material science, bio-geo-engineering, artificial intelligence, and unmanned aircraft systems. In less than five years, the program has stimulated wide research interest in the field of WM, specifically rainfall enhancement, among the international scientific community. The projects have produced state-of-the-art measurements, advanced numerical models, innovative prototypes, and proof-of-concept field demonstrations. Furthermore, the use of field operational programs as a platform for basic research efforts continues to be an excellent opportunity for both scientists and students to conduct a broad range of studies and enhance the knowledge base of RE, as well as the aerosol–cloud interaction which are among the least understood physical processes in weather and climate models.

Confronting already existing or imminent water shortages, meteorologists and their national meteorological services in semi-arid regions can explore the scientific basis for carrying out RE projects. In this connection, they can inform their governments that the United Nations Convention to Combat Desertification (Art.17) also mentions RE as one of the methods for water management. Advances and limitations of RE should be clearly stated. Only well-informed governments and/or communities will provide adequate funding needed for the beneficial application of WM projects.

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