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Review of Advances in Precipitation Enhancement Research

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Abstract

This paper provides a summary of the assessment report of the World Meteorological Organization (WMO) Expert Team on Weather Modification that discusses recent progress on precipitation enhancement research.

The progress has been underpinned by advances in our understanding of cloud processes and interactions between clouds and their environment which, in turn, have been enabled by substantial developments in technical capabilities to both observe and simulate clouds from the microphysical to the mesoscale.

We focus on the two cloud types most seeded in the past: winter orographic cloud systems and convective cloud systems. A key issue for cloud seeding is the extension from cloud-scale research to water catchment-scale impacts on precipitation on the ground. Consequently, the requirements for the design, implementation and evaluation of a catchment-scale precipitation enhancement campaign are discussed.

The paper concludes by indicating the most important gaps in our knowledge. Some recommendations regarding the most urgent research topics are given to stimulate further research.

49 **Capsules**

50 The World Meteorological Organization (WMO) Expert Team on Weather
51 Modification has assessed recent progress on precipitation enhancement
52 research.

53

54

1. Introduction

In response to shortages of reliable water resources and other societal needs, often amplified in a changing climate, an increasing number of countries are now planning or actually conducting precipitation enhancement activities. As sometimes desperate activities are based on empty promises rather than sound science, the World Meteorological Organization (WMO) Expert Team on Weather Modification recently reviewed progress on precipitation enhancement research since the last assessments published in WMO workshop reports (WMO 2000, 2010) and in a USA National Research Council report (2003). The main findings and recommendations from this new WMO peer-reviewed report (2018a) are summarized below. The annex of the WMO report lists some of the science-based cloud seeding activities carried out across the world. In order to limit the length of the text in this summary, the list of references is not exhaustive but highlights a few recent publications. A more complete list of references can be found in WMO (2018a).

In the last two decades, there have been major developments in modelling, analytical and observational capabilities, furthering our understanding of individual cloud processes and their potential interactions. Due to numerous aerosol-cloud interaction studies for climate purposes, we better understand now that, when serving as cloud condensation nuclei (CCN) and ice nucleating particles (INP), the ambient

aerosol particles influence the number and size distribution of the hydrometeors and consequently the chain of precipitation mechanisms. The huge energy associated with natural cloud systems means that any attempt to enhance precipitation at the ground must be based on a precise knowledge of the system and it must involve a careful intervention (such as seeding with appropriate aerosol particles that augment or substitute for natural particles) that takes advantage of a “surgical” opportunity for some clouds.

This paper focuses exclusively on the scientific basis of precipitation enhancement: hail suppression, fog dispersion or harvesting as well as subjects related to geoengineering are not discussed. We consider the two cloud types most seeded in the past: winter orographic clouds and convective clouds. The seeding of wintertime orographic clouds with glaciogenic seeding particles has the potential to trigger snowfall, in order to increase snowpack in mountainous water reservoir regions. The second type concerns liquid and mixed phase convective clouds that are seeded with hygroscopic or glaciogenic particles in order to trigger liquid or mixed phase precipitation.

2. Natural cloud systems and their variability

2.1 Microphysics of clouds

103 Aerosol particles are ubiquitous, and they vary in size from a few
104 nanometres to tens of micrometres. They are essential for the formation
105 of clouds as they provide the surface on which liquid condensation or solid
106 deposition commences. The basis for most cloud seeding is the addition of
107 specific aerosol particles that compete with the naturally available
108 particles for water vapour.

109 From Köhler theory (Pruppacher and Klett 1997) the nucleation of droplets
110 on a subset of available aerosol particles (CCN) is relatively well
111 understood as a function of their size distribution, chemical composition,
112 updraft velocity and resulting supersaturation.

113

114 In order to form ice crystals outside the homogeneous (without any solid
115 nucleating surface) nucleation region ($T < -35^{\circ}\text{C}$) another subset of aerosol
116 particles (INP) are necessary. In their presence, ice can form by
117 deposition nucleation from vapour or by freezing nucleation from liquid
118 (Vali et al. 2015). The number concentration of INP increases rapidly with
119 decreasing temperature and increasing supersaturation (Pruppacher and
120 Klett 1997). However, our current understanding of nucleation processes
121 is limited, and we cannot use the aerosol particle number concentration
122 and chemistry to precisely predict INP concentration or even the specific
123 ice formation mechanism (Hoose and Möhler 2012; Kanji et al. 2017).
124 Owing to an absence of reliable monitoring of INP concentration and
125 composition, these limitations result in uncertainties in the spatial and
126 temporal variability of natural INP.

A further difficulty in relating observed ice number concentration to INP arises in some clouds from ice multiplication processes (Field et al. 2017) that can occur naturally in specific temperature ranges, or as an artefact during sampling (Baumgardner et al. 2017).

Nucleated liquid cloud particles may grow to precipitation-sized drops through condensation and then collision-coalescence processes. The collision efficiency depends strongly on the difference between terminal velocities of drops, and hence on the drop size distribution (Twomey, 1977). The transition from droplets to raindrops is efficient when nucleation occurs on few CCN with a large variance in their sizes. On the other hand, many small droplets with a narrow size distribution will often be activated in a polluted environment, decreasing the likelihood of collision and coalescence and resulting potentially in a reduction in the efficiency of the transition to rain (e.g., Flossmann and Wobrock 2010).

For clouds that extend into or develop above the freezing level, additional processes contribute to the formation and growth of mixed-phase and ice hydrometeors. Following nucleation, ice particles grow by vapour diffusion, leading to rapid depositional growth while there is liquid water to evaporate and maintain the supersaturation conditions for ice (the Wegener-Bergeron-Findeisen process: WBF; Pruppacher and Klett 1997).

In summary, water vapour diffusion alone is often not efficient enough to generate precipitation within the lifetime of a cloud, and so collision and coalescence between droplets are essential to produce precipitation-sized drops. In addition, supercooled drops can be captured and frozen (completely or partially) by ice crystals. The resulting frozen particles can grow by riming or mixed phase processes to form graupel or hail. The ice particles themselves can collide to form aggregates. All these processes are influenced by the size and dynamics of the hydrometeors, as well as environmental factors, such as the surrounding water vapour and electric fields (Pruppacher and Klett 1997).

2.2 Dynamics of the cloud systems of interest in precipitation enhancement

Wintertime frontal systems passing over mountainous areas generally show greater precipitation on the windward side than on the leeward side. Even in essentially stratiform clouds, convection is often embedded in these cloud systems. On many occasions the low-level stratification and winds are such that the air rises over (rather than moves around) the orography. The rising moist air on the windward side generates condensation or freezing. Provided that the freezing level is below the peak of the ranges and that the temperatures around the peak of the ranges are not too low, supercooled liquid water (SLW) rather than ice particles tend to be generated.

The distribution of orographic precipitation is controlled by microphysical processes, airflow dynamics, and moist-air thermodynamics (Houze 2012). Watson and Lane (2014) and Geerts et al. (2015) demonstrate that orographic precipitation is sensitive to the terrain geometry (aspect ratio) and the low-level stability of the flow (Froude number). Thus, provided that any embedded convection is not too intense, the spatial and temporal distribution of precipitation on the ground can be estimated with some accuracy.

Surface heating is usually significant in the generation of *convective cloud systems* suitable for seeding. There is a wide range in the scale of convective cloud systems that have been seeded, extending “from small fair-weather cumulus (with spatial scale of a few kilometres and lifetime of tens of minutes) to deep cumulus or deep thunderstorms and mesoscale convective complexes (100 km wide and timescale of several hours)” (WMO 2018a). In order to be a candidate for hygroscopic seeding, liquid-cloud processes need to be important in the initial development of these clouds, with a substantial depth between cloud base and the freezing level. Convection in these clouds can be enhanced by the release of latent heat, as CCN and INP concentrations will influence the development of the cloud microphysics. In particular, cloud droplets can be converted to ice particles, when the clouds rise above the freezing level.

Convective clouds are greatly influenced by surface fluxes, boundary layer dynamics, entrainment, wind shear, moisture availability and the strength

of capping inversions. They develop precipitation that is highly variable in space and time, and this variability of the natural precipitation provides a challenge for the detection of any increase in local precipitation due to cloud seeding.

3. Potential for precipitation enhancement

Table 1 summarizes the main published seeding methods used for precipitation enhancement. Some comments in Table 1 are discussed further in the following text. The figures 1, 2 and 3 support visually the description.

3.1 Winter orographic cloud systems

Tessendorf et al. (2019) summarise the progress that has been made in recent years on orographic cloud seeding. For wintertime orographic clouds, precipitation is influenced by the local orography, with SLW being generated as moist air near the freezing level rises over the ranges. The basic hypothesis of orographic cloud seeding is that the introduction of artificial INP (usually silver iodide, AgI) to the orographically-generated SLW promotes the formation of ice particles at relatively warm (around -5 °C) temperatures, and that these particles subsequently grow by deposition and collision leading to enhanced precipitation on the ground over the ranges (see figure 1a and b for a schematic illustration). This

glaciogenic seeding hypothesis has been confirmed by observational and modelling research (French et al. 2018).

Geerts et al. (2010) follow the impact of ground-based seeding of AgI particles on the microphysics of orographic clouds associated with the Wyoming Weather Modification Pilot Project (WWMPP; Breed et al. 2014). The seeding impact is identified by comparing the radar data from seeded and unseeded flight legs using contoured frequency – altitude displays (CFADs), developed by Yuter and Houze (1995). The impact of seeding shown by the CFADs increases with Froude number, that is with decreasing flow stability. Building on such studies, French et al. (2018) provide a detailed record of the processes associated with the enhancement of precipitation from wintertime orographic cloud systems for the mountain ranges of south western Idaho, USA.

French et al. (2018) describe two strategies for aircraft-based seeding with AgI. For the burn-in-place strategy, the seeding aircraft flies at the height where seeding is expected to be effective. In this approach, the artificial INP are transported essentially horizontally into the cloud from the aircraft using acetone burners or burn-in-place flares. The second strategy has the seeding aircraft deploying ejectable flares at or above the height that contains the supercooled water. This approach is clearly advantageous in mountainous terrain, but the flares may burn out before falling to the optimal level if the aircraft is too high.

A third strategy for the injection of seeding material into cloud involves various ground-based techniques. In addition to ground-based acetone burners, artillery shells and rockets (including high-altitude fireworks) have been used for cloud seeding (Abshaev et al. 2006). The challenge for all ground-based techniques is to ensure that the INP reach the appropriate cloud level for seeding. Remote sensing (Tessendorf et al. 2019) allows to follow the propagation of the seeded material in the cloud. Observation and modelling studies (Bruitjes et al. 1995; Xue et al. 2013) suggest that direct seeding strategies are more effective than ground-based generators.

3.2 Convective cloud systems

For convective clouds driven by surface heating, the complex interactions between dynamics and microphysics can lead to a variety of potential opportunities to enhance precipitation. Two main strategies are commonly used to seed these clouds. Hygroscopic seeding involves the introduction of (generally large) CCN to enhance the formation of large drops near cloud base and to activate coalescence processes. Glaciogenic seeding involves the introduction of INP in order to promote ice and mixed phase processes.

Hygroscopic seeding particles tend to be salts with sizes in the range of 0.1-10 μm (e.g., Segal et al. 2004; Drofa et al. 2013), and they are

dispersed from an aircraft as micro-powders, through burn-in-place flares (Bruinjes et al. 2012) or through ejectable flares. Ground based flares, ground-based rockets and artillery shells can also be used to disperse seeding material into convective clouds (Abshaev et al. 2014). This seeding approach is potentially applicable to cloud systems with more than about 1 km of cloud depth below the freezing level (Silverman and Sukarnjanaset 2000), with a lack of large CCN in the natural aerosol particles, and with updrafts near cloud base exceeding 1 m/s (Tessendorf et al. 2012). Seeding particles that are larger and more hygroscopic than the background particles are expected to grow more rapidly through condensation and subsequently through collision with other droplets (see figure 2 for a schematic illustration). In addition to this 'tail' effect, such artificial CCN also have the 'competition' effect of preventing the nucleation of small or less soluble CCN (Segal et al. 2007) by suppressing the peak supersaturation in the cloud.

If the cloud depth extends above the freezing level, then the effects of artificial CCN from the warm phase can extend into the mixed and ice phases of cloud (Lawson et al. 2015). A number of research experiments in different countries suggest that hygroscopic seeding might increase rainfall from continental storms (e.g., Prabha et al. 2011; Tessendorf et al. 2012).

For *glaciogenic seeding*, materials such as AgI and dry ice are injected into cloud in order either to increase the concentration of INP (as in

seeding wintertime orographic cloud) or to increase the buoyancy of the cloud through the release of latent heat from the freezing of SLW (see figure 3 for a schematic illustration). As the introduction of ice particles ('static' effect) leads to increased latent heat release ('buoyancy' effect), both effects are expected to occur simultaneously.

When seeding of convective cloud systems extends into the regime of mixed-phase processes the interactions between cloud dynamics, cloud microphysics and cloud environment (entrainment) become still more complex. Despite numerous experiments over several decades, the documenting and understanding of the chain of processes from aerosol particles to precipitation on the ground remain outstanding. For example, merging of individual clouds is known to lead to a substantial increase in precipitation, maximum cloud area, radar echo top and maximum radar reflectivity (e.g., Popov and Sinkevich 2017). However, the influence of seeding on these processes are not well understood or even well documented.

4. Advances in observations

There have been great advances in technologies for observing clouds in recent decades, especially in ground-based, aircraft-based and satellite-based remote sensing, and these technologies have played a major role in furthering our understanding of the physical processes associated with

precipitation enhancement. Laboratory measurements also provide important support for precipitation enhancement research (WMO 2018a).

4.1 Precipitation on the ground

Accurate observation of the natural precipitation and any artificial enhancement is essential to precipitation enhancement research. However, this remains a challenge due to the high spatial and temporal variability of precipitation, especially in convective systems. Ground-based precipitation gauges provide the most accurate measurements of precipitation over a catchment-scale area. Villarini et al. (2008) confirm that sampling errors for precipitation increase as the temporal integration time decreases. The specified periods when seeding may occur in a cloud seeding project are known as experimental units (EUs), and they can currently be as short as a few hours (Manton et al. 2011; Breed et al. 2014). The uncertainties associated with precipitation measurements over an EU duration need to be taken into account when evaluating cloud seeding projects.

Measurement uncertainties are greatly increased when precipitation falls as snow. Rasmussen et al. (2012) summarise the current state of knowledge in snowfall measurement, where strong winds and turbulence lead to substantial under-catch. They recognise that the benchmark Double Fence Intercomparison Reference wind shield is not always

feasible at remote sites, and so understanding the uncertainties of sub-optimal but practical techniques is essential. Indeed Kochendorfer et al. (2018) use results from the World Meteorological Organization Solid Precipitation Intercomparison Experiment (WMO-SPICE) to show that the more effective the wind shield the more accurate are bias adjustments for under-catch.

Scanning radars can be used to estimate precipitation over a large area, especially where the terrain is steep and rough. While progress continues to be made in reducing the uncertainties from radar reflectivity (e.g., Hasan et al. 2016), the application of dual-polarisation radar to precipitation estimation has been a major development (Brandes et al. 2002), so that information on hydrometeor phase and shape can be used when calibrating radars against local disdrometers.

Krajewski et al. (2010) identify improvements in radar-based estimates of precipitation over the last forty years. They find that the mean difference between radar and rain gauges has been reduced by about 21%, but there is little change in the difference when the estimates are bias-adjusted. Indeed, they note that “the comprehensive characterization of uncertainty of radar-rainfall estimation has not been achieved.” However, most recent work in this area has been focused on precipitation estimation with a multi-sensor approach in which radar, rain gauge and satellite data

are used together, especially for convective precipitation (Zhang et al. 2016).

4.2 Synoptic environment

The development of a cloud system, especially for winter orographic clouds, is substantially controlled by the synoptic environment, which generally determines when clouds are suitable for seeding. Routine operational analysis and prediction systems provide essential information on these conditions, but they should be supplemented by dedicated upper-air soundings during cloud seeding projects (Manton et al. 2011; Breed et al. 2014). These data can be supplemented by microwave radiometers and wind profilers to yield additional information on local temperature, humidity and wind profiles.

4.3 Cloud dynamics

For some decades, software systems (Dixon and Wiener 1993; Abshaev et al. 2010) have provided detailed information on the initiation and development of cloud cells, based on radar reflectivity only. Advances in Doppler and dual-polarisation capabilities have led to major improvements in the observation of the dynamics of clouds. Pokharel et al. (2014) show that seeding-induced changes in cloud structure can be identified through a combination of aircraft-based and ground-based radars. Portable X-band

Doppler-on-Wheels radars (French et al. 2018) and K-band micro rain radars (Maahn and Kollias, 2012) can be used in mountainous terrain to provide comprehensive information on the evolution of cloud systems in seeded and unseeded conditions. Imaging radars (generally using phased array methods) are being developed to yield three-dimensional data with scan times on the order of 10 s (e.g., Kurdzo et al. 2017).

Radars are complemented by the recent generation of geostationary satellites in providing information on cloud structure and microphysics to support decision making and analysis in cloud seeding projects. These satellites have spatial resolution of about 1 km, around 16 spectral channels, and scanning intervals on the order of 10 minutes (Bessho et al. 2016; Schmit et al. 2017).

4.4 Microphysics

As precipitation enhancement involves the inducement of changes in cloud microphysics, comprehensive and systematic measurements must be taken to identify the chain of processes extending from aerosol properties to precipitation at the ground.

Cloud seeding involves the introduction of artificial CCN or INP. Thus, measurements of the properties of aerosol particles in both seeded and unseeded areas are necessary. The optical and electrical mobility

properties of particles can be used to monitor the aerosol size distribution from aircraft (Wang et al. 2012). A particular challenge arises with the measurement of INP. Here, also complementary laboratory studies are essential to identify the underlying processes of ice nucleation and multiplication.

Precipitation enhancement often involves the transformation of SLW to ice, and so detailed measurement of SLW is needed for research as well as for any operational cloud seeding. Total liquid water path is effectively measured by microwave radiometry (Osburn et al. 2016), except when rain affects the radiometer radome (Araki et al. 2015).

Aircraft-based (Geerts et al. 2010; French et al. 2018) and ground-based (Delanoë et al. 2016) radars and lidars can readily identify changes in cloud microphysics from unseeded to seeded conditions. However, *in situ* measurements are needed to obtain detailed information on hydrometeors. A challenge arises from the large range of hydrometeors in size, shape and concentration. Forward-scattering and particle-imaging probes are used to take *in situ* measurements of cloud droplets, ice particles and raindrops that extend in size from 2 to 10,000 μm . The formation of drizzle requires accurate measurement of large particles at low concentrations (Baumgardner et al. 2017); this is especially important in hygroscopic cloud seeding where large drops in the tail of the cloud drop distribution play an essential role in the development of precipitation.

Baumgardner et al. (2017) also describe the challenges associated with the shattering of ice particles as they impact the measuring instrument, leading to bias in the measurement of small particles. A range of airborne probes is therefore needed to properly support a cloud seeding programme. For a list of current *in situ* cloud particle probes see Baumgardner et al. (2017, their Table 9-1).

5. Advances in modelling

In recent years there has been significant progress in the modelling of clouds. Ready access to models like the Weather Research and Forecasting (WRF) Model (Liu et al. 2008) means that three-dimensional mesoscale modelling of entire cloud systems embedded in a large-scale flow is now standard practice. These models are driven by numerical weather prediction (NWP) model output, with nesting capabilities that support zooming into a region of interest at grid sizes approaching Large-Eddy Simulation (LES) scales (Chu et al. 2017a; 2017b; Xue et al. 2016). The models include multi-moment or bin-resolved microphysics schemes. Model complexity can be further increased by combining the atmospheric model results with snowpack, snowmelt and runoff models (Yoshida et al. 2009) to assess the impact of seeding on seasonal time scales.

5.1 Modelling of Microphysics

For precipitation enhancement research, the cloud microphysical parameterization is critical as it greatly affects the accuracy of numerical model seeding experiments. Various cloud microphysical parameterizations are currently coupled to non-hydrostatic models (NHMs). For bulk cloud microphysical parameterizations, hydrometeors are separated into distinct categories and the size distribution of each category is represented by an inverse exponential function or a gamma function. The change in the total mass, total number and/or radar reflectivity (single, double or third moment bulk schemes) of the particles in each category is predicted (e.g., Khain et al. 2015; Lompar et al. 2017). More detailed approaches have been proposed by Saleeby and Cotton (2004) or Morrison and Milbrandt (2015), e.g.

For bin spectral microphysical parameterizations, the change in hydrometeor size distribution is simulated in detail: each category is divided into several size ranges (bins), and the change in particle number (single-moment scheme) or in particle number and mass (double-moment scheme) is calculated for each bin of each category. Such models allow explicit representation of the nucleation of water drops and ice particles on an ambient aerosol population and more realistically simulate clouds under differing pollution conditions (e.g. Planche et al. 2010). Moreover, the nucleation of ice particles through different INP modes can now be considered (Hiron and Flossmann 2015). Some bin microphysics models

even include a bin-resolved representation of aerosol particles (e.g., Flossmann and Wobrock 2010).

An outstanding source of uncertainty in cloud models is the sensitivity of the results to variations in microphysics parameterizations (Geresdi et al. 2017). Sensitivities are found for both bin microphysics (Khain et al. 2015) and bulk models (Morrison and Grabowski 2007). Model intercomparison studies may help resolve these uncertainties, especially if they are accompanied by detailed field observations that can validate the simulated processes.

5.2 Modelling of seeding

A key assumption of cloud seeding is that the seeding particles dominate over the effects of the natural aerosol. However, most NWP models currently do not consider the ambient background aerosol population when calculating water drop and ice particle nucleation, and so this deficiency limits their usefulness for cloud seeding simulations where the competition between the natural and seeding aerosols is essential.

Numerical modelling of seeding with dry ice or AgI is currently practical, but there remains uncertainty in the modelling of liquid CO₂ (e.g., Xue et al. 2013; Geresdi et al. 2017). On the other hand, current AgI seeding schemes in models are based on experimental results from the 1990s and

do not reflect advances in knowledge since that time; for example, they do not take into account the potential for INP to act also as CCN.

It is generally found from model simulations that hygroscopic particles need to be larger than about a micrometre in order to generate raindrops (e.g., Segal et al. 2004). It follows that salt micro-powder seeding of warm clouds is usually more effective than hygroscopic flare seeding (Kuba and Murakami 2010). However, the effect of hygroscopic seeding on rainfall on the ground is found to be dependent on details such as the type of cloud and the type of seeding material. Consequently, consistent results from modelling are still lacking. The application of three-dimensional NHMs to hygroscopic seeding has been limited, and the hygroscopic seeding schemes in NHMs have been rather crude. For example, a model seeding scheme should account for the CCN and INP capabilities of particles generated from the combustion agent of hygroscopic flares as well as the capabilities of the anti-caking agents included in the salt micro-powder. Moreover, the dispersion of both hygroscopic and glaciogenic seeding materials tends to be over-estimated because of the relatively coarse resolution of current 3D NHMs. This problem can be alleviated through the use of LES models for cloud seeding simulations, in order to follow accurately the dispersion of the seeding material.

6. Catchment-scale research projects

530

531 Comprehensive field programs and modelling studies have now shown
532 that cloud seeding can affect the development of precipitation in some
533 cloud systems. However, these effects need to act over substantial time
534 periods and spatial regions in order to accrue economic and societal value.
535 That is, it is necessary to extend the seeding effects documented in
536 individual clouds to areas comparable with water catchments and over
537 seasonal or longer time scales.

538

539 Three major catchment-scale experiments are reported in the recent
540 scientific literature. The Snowy Precipitation Enhancement Research
541 Project (SPERP) in the Snowy Mountains of south eastern Australia had
542 two phases: SPERP-1 from 2005 to 2009 (Manton et al. 2011) and SPERP-
543 2 from 2010 to 2013 (Manton et al. 2017). With two sites in Wyoming,
544 USA, the Wyoming Weather Modification Pilot Project (WWMPP) ran from
545 2008 to 2014 (Breed et al. 2014; Rasmussen et al. 2018). The Israel-4
546 experiment commenced in northern Israel in 2013 (Freud et al. 2015).
547 While other catchment-scale experiments have been or are currently
548 being carried out in other countries (WMO 2018a), we focus below on
549 these three experiments.

550

551 Weather modification has had a colourful history (Fleming 2010), largely
552 because it is difficult to conclusively detect the enhancement of
553 precipitation on the ground over a significant area and time period. Such

detection requires careful statistical analysis over many EUs. A statistically robust and efficient analysis in turn requires the experimental procedure to be consistently maintained over the duration of the project. The inclination of a scientist to adjust an experiment in the light of new knowledge can thus jeopardise the outcome of a precipitation enhancement project.

6.1 Economic issues

Increased water on the ground is the basis of the economic benefit of precipitation enhancement. However, the scientific justification for any economic benefit depends upon understanding of the chain of physical interactions extending across a large range of spatial and temporal scales. The design of an experiment that scales up from earlier exploratory studies should account for the interactions between all these scales.

Convective clouds pose a major challenge for scaling up from exploratory studies. For example, Terblanche et al. (2000) showed that scaling up the apparently positive impact of seeding at storm scales to what would be required to achieve catchment-scale impacts led to a “two orders of magnitude challenge”, as about 6000 storms would need to be seeded. Similarly, Silverman and Sukarnjanaset (2000) found that the methodology of seeding individual mixed-phase clouds is unlikely to be economically viable. Further studies by Terblanche et al. (2005) and

Shippey et al. (2004) also concluded that more efficient ways to deliver seeding material into clouds would be required to achieve impacts at catchment scales.

In estimating the economic benefit of cloud seeding, it is necessary to also account both for the benefits of additional water over the seeded area and for the total costs of a continuing operational project. Those costs include actions needed to obviate any potential environmental risks (WMO 2018a).

6.2 Preliminary studies

A catchment-scale project typically is preceded by a series of exploratory studies to characterise the clouds of the region of interest and to assess their suitability for seeding. For example, Koshida et al. (2012) investigate the suitability of clouds in Japan for hygroscopic and glaciogenic seeding, and Geerts et al. (2010) report on aircraft-based observations of glaciogenic seeding in the mountains of Wyoming, USA. Observational and modelling studies should be carried out on wintertime orographic clouds to ensure that SLW occurs at least upwind of the mountains.

Similar studies are also needed for convective clouds (especially with mixed-phase) to explore the relationships between the local aerosol particles and cloud microphysics. The Cloud Aerosol Interaction and

Precipitation Enhancement Experiment (CAIPEEX) investigates warm and mixed-phase convective clouds during the Indian monsoon season (Prabha et al. 2011; Kulkarni et al. 2012) as a basis for cloud seeding. Preliminary results show that pollution aerosols over continental areas tend to increase the depth of cloud and hence to delay the onset of warm rain.

Field and modelling studies are required to determine the optimal seeding strategy. This strategy is dependent upon factors such as the availability of seeding material and associated infrastructure, as well as studies to ensure that the seeding material will reach the appropriate part of clouds with a proper dosage within a reasonable time.

Once it is clear that clouds suitable for seeding occur in the region of interest, seeding simulations using historical climate data should be carried out to test whether the impact of seeding is likely to be detected within a few years (e.g., Manton et al. 2011). The probability of detection increases with the number of seedable events and the expected seeding impact. Modelling studies (Ritzman et al. 2015) have also been used to estimate seeding opportunities.

6.3 Randomised design

The duration of an EU is limited by the nature of the local precipitation and the available infrastructure. Owing to limitations on the availability of

precipitation data, EUs in the past tended to be at least one day in duration. More recently, short-term precipitation is readily recorded and monitored, so that the duration of an EU is decided by the expected duration of consistent conditions for cloud seeding; for example, 4-hour EUs were used for WWMPP (Breed et al. 2014).

A key challenge for catchment-scale projects is that the signal-to-noise ratio is invariably very small. This difficulty arises because the natural variability of precipitation is high (especially for short-term EUs), while the average impact of seeding is relatively low (below 20%). The design of a catchment-scale project therefore needs to include a randomisation process to select which EUs are seeded and which are not seeded (unseeded). As with medical trials, scientists involved with decision making for the project should not be aware of the seeding sequence. An important decision of the randomisation process is the specification of the seeding ratio: the ratio of the number of seeded events to the number of unseeded events. A seeding ratio larger than one leads to the range of environmental conditions for unseeded EUs being smaller than for seeded EUs, causing greater statistical uncertainty (Manton and Warren 2011).

A catchment-scale project aims to enhance precipitation in a target area of at least 1000 km². It is usual to also identify a control area, that is used to predict the natural precipitation in the target area. A control area must have precipitation that is highly correlated with that in the target area (so that the control is an effective predictor of target precipitation), and the

control area must not be impacted by seeding material (so that it represents the natural precipitation of the target). A range of target-control configurations is used: fixed target and control areas are used in SPERP, crossover target and control is used in WWMPP, and a single area is used for target and control in Israel-4 (Freud et al. 2015). Each configuration has challenges: finding a suitable control can be difficult for fixed target-control; inadvertent contamination of the control area is likely for a crossover design; ensuring equivalent synoptic conditions across seeded and unseeded EUs is difficult for single area designs.

6.4 Seedability conditions

Especially for short-duration EUs, it is essential to have well-defined environmental conditions for starting an EU. For glaciogenic seeding, these seeding criteria need to ensure that SLW is available, that seeding material will disperse to the SLW, that ice particles nucleated by the seeding material will grow sufficiently to ultimately fall into the target area, that suitable conditions for seeding will persist for the duration of an EU, and that material from a seeded EU will not contaminate a following unseeded EU. Preliminary observational and modelling studies provide the basis for the specification of the seedability conditions (e.g., Manton et al. 2011; Breed et al. 2014; Freud et al. 2015). Cloud seeding operations should also be supported by model-based forecasts (Murakami et al. 2011; Breed et al. 2014; Hashimoto et al. 2017; French et al. 2015).

674

675 **6.5 Indicators of seeding impact**

676

677 It is essential to initially specify indicators of seeding impact that assess
678 the success of a catchment-scale experiment across all EUs. The large
679 number of potential indicators means that statistical multiplicity (where
680 the application of several statistical tests can lead to some positive results
681 by chance) can be a problem for cloud seeding experiments. The problem
682 is overcome by specifying a small number of primary indicators to assess
683 success, while listing a range of secondary indicators to provide
684 supplementary evidence on the physical basis of the primary indicators.
685 For example, Manton et al. (2011) specify two primary indicators for
686 SPERP-1: one related to targeting of seeding material and the other
687 related to the average enhancement of precipitation. Estimates of the
688 increase in natural precipitation of suitable clouds vary from a negligible
689 fraction to over 20% (Ryan and King 1997). Manton et al. (2017) suggest
690 that substantial uncertainty in these estimates arises from the methods
691 used to estimate the natural precipitation in the target area.

692

693 The number of potential secondary indicators is limited only by the range
694 of observing systems used in an experiment. We distinguish between
695 indicators based on data observed consistently for each EU (for example,
696 the ordered residual diagrams of Manton et al. (2017) showing systematic
697 seeding impacts) and those based on data observed during special

observing periods (for example, the aircraft data of Miao and Geerts (2013) showing changes in cloud microphysics due to seeding in some EUs).

7. Conclusions and recommendations

Recognising the impacts of climate change and the increasing scarcity of reliable water resources, the World Meteorological Organization (WMO) Expert Team on Weather Modification has reviewed the progress made on the scientific aspect of precipitation enhancement (WMO 2018a).

Exploiting the insight gained by aerosol-cloud-climate research regarding the role of aerosol particles, sophisticated remote sensing and *in situ* observational capacities, and increasing computer power, we have significantly advanced our understanding of cloud processes in the global water cycle as well as on a regional and local scale, even though gaps remain.

The distribution of natural precipitation in wintertime orographic clouds suitable for seeding is largely determined by the orography interacting with synoptic-scale systems. Thus, the spatial and temporal distribution of precipitation on the ground can often be estimated with sufficient accuracy to allow the impact of seeding to be quantified. Seeding with glaciogenic particles near mountainous water catchments aims to convert orographically-induced supercooled liquid water to ice, which in turn leads

to snowfall and increased precipitation on the ground. Careful analysis of randomized campaigns identifies a possible increase of precipitation ranging from essentially zero to more than 20%. Higher values tend to be associated with aircraft-based seeding using AgI. However, the reasons for the large variation in impacts are not well understood and estimates of impact are sensitive to the estimation of the natural precipitation in the target area. The most promising results are obtained for clouds that have already a natural tendency for precipitation formation (WMO 2018a).

Mixed phase convective clouds have also been seeded with hygroscopic or glaciogenic particles with the aim of triggering liquid or mixed phase precipitation. As these clouds are generally driven by surface heating, the variability of their natural precipitation means that it is difficult to identify any increase in local precipitation due to seeding. Moreover, when seeding mixed-phase clouds, the interactions between clouds must be followed, because the main effects of the seeding can occur some hours after seeding in distant clouds spawned by earlier clouds. The complexity of cloud systems means that any seeding strategy requires a precise knowledge of the system and a careful injection of appropriate aerosol particles that augment or substitute for natural particles to enhance the natural precipitation.

Exploratory studies are needed to document the processes associated with natural precipitation in the region of interest and to estimate their

sensitivity to seeding. Once the range of exploratory studies has been completed and deemed successful, the seeding can be extended to larger areas and time periods to obtain an economic benefit. This upscaling of an exploratory seeding campaign to a catchment basin-sized region requires again a strict protocol. Before a catchment-scale experiment is undertaken, historical data should be analysed to estimate the probability of detection of enhanced precipitation, that is, to determine the minimum duration of the experiment. Randomization of seeding and a consistent methodology are essential to support a rigorous statistical analysis of the data collected during an experiment. High-resolution modelling can be used to support all phases of an experiment. Furthermore, possible toxicological, ecological, sociological and legal issues, as well as extra-area effects need to be considered.

There have been advances in our understanding of a cloud within its synoptic environment. However, there remain unresolved issues associated with the interactions between the natural aerosol particles (that provide the CCN and INP for hydrometeors), cloud microphysics and cloud dynamics.

Our knowledge of microphysical processes remains incomplete, especially on the formation and growth of solid hydrometeors. In particular, the basis of secondary ice multiplication processes in cloud is poorly understood. The interactions between cloud microphysics and dynamics and their consequences for the precipitation efficiency, as well as with the

770 dynamics regarding all scales, need to be further investigated. The
771 location, timing and methodology of seeding have to be adapted to the
772 local conditions. Observation capacities (including robust open-source
773 software) as well as high resolution, three-dimensional mesoscale
774 modelling of dynamics, microphysics and aerosol processes need to be
775 advanced, particularly in relation to competition between natural and
776 seeded particles. Model intercomparison projects would identify optimal
777 approaches to modelling cloud microphysics. These projects should include
778 observational datasets obtained during measurement campaigns.

779

780 The uncertainties that limit the scientific foundation for cloud seeding,
781 especially for mixed-phase convective clouds, will be reduced through
782 international analysis and model intercomparison workshops (McFarquhar
783 et al. 2017; Grabowski 2015), promotion of best-practice, and the
784 publication of the data and results of relevant research in the international
785 scientific literature.

786 While water shortage has motivated cloud seeding initiatives in the past,
787 accelerating climate change has added a renewed urgency, but also an
788 additional complexity due to the uncertain regionalisation of its effects.

789

790 The recommendations in the AMS Statement on Planned Weather
791 Modification through Cloud Seeding
792 ([https://www.ametsoc.org/index.cfm/ams/about-ams/ams-](https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/statements-of-the-ams-in-force/planned-weather-)
793 [statements/statements-of-the-ams-in-force/planned-weather-](https://www.ametsoc.org/index.cfm/ams/about-ams/ams-statements/statements-of-the-ams-in-force/planned-weather-)

modification-through-cloud-seeding/) are supported by the findings of this assessment. More detailed references on the science of cloud seeding are given in WMO (2018a).

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Table 1: Compilation of current seeding methods, including comments on some of the methods (more references can be found in WMO (2018a).

Seeding agent	Hypothesized functioning and delivery method	Some method details and comments	Some recent references (for more references see WMO (2018a))
AgI, AgIO ₃	Glaciogenic seeding, aircraft, ground burner, rocket, cannon; pyrotechnic flares with 10 to 100 g of seeding agent per minute	Mean size of 0.1µm; can also act as CCN in liquid clouds	Abshaev, M.T. et al. 2006 ; Dessens et al. 2016
Liquid CO ₂	Glaciogenic seeding, aircraft	Cools down to -80°C and triggers homogeneous nucleation	Seto et al. 2011
Dry ice (solid CO ₂)	Glaciogenic seeding, aircraft	Pelletized (diameters of 0.6 to 1 cm and 0.6 to 2.5 cm) or small	Seto et al. 2011

		particles	
Hygroscopic flares	Hygroscopic seeding; aircraft	Sodium chloride, potassium chloride, or calcium chloride particles; size range 0.1-10 μm diameter	Ghosh et al. 2016 ; Brintjes et al. 2012
Micro-powders	Hygroscopic seeding, aircraft	Optimum suggested size of NaCl crystals is 7.5-10 μm	Drofa et al. 2013
Core/shell NaCl/TiO ₂ (CSNT) particle	Hygroscopic seeding	Adsorbes ~295 times more water vapor at 20% RH than NaCl	Tai et al. 2017
Ionization of aerosols and clouds	Negative ions are generated from a corona discharge wire array; the ions become then attached to particles in the	No scientific basis that this could increase precipitation	Tan et al. 2016

	atmosphere, which later act as CCN		
Electrification of clouds	Electric discharges under certain conditions can lead to temperature increase of drop freezing	No studies have addressed quantitatively how this would impact precipitation at the surface	Adzhiev and Kalov, 2015
Laser- induced condensation	Triggering condensation in sub-saturated conditions	Condensation has been shown to occur on very local scales; problem of converting droplets into precipitation in a dry atmosphere remains unaddressed	Leisner et al. 2013
Hail or acoustic cannon	Shock wave generator using a mixture of	No scientific basis	Wieringa and Holleman, 2006

	acetylene and oxygen to increase collision coalescence growth of water droplets		
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1268 Figure Caption list:

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1270 Figure 1 (a) glaciogenic seeding of an orographic winter time cloud; in
1271 red: the supercooled seeded area and the seeding material to be added by
1272 plane, burner or rocket; (b) the intended outcome of the seeding in red,
1273 when the added INP form crystals that grow via WBF effect and riming to
1274 form snow; the additional release of latent heat may invigorate the cloud;
1275 the arrow indicates the sense of the space and time evolution.

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1278 Figure 2 (a) hygroscopic seeding of a convective cloud; in red: the seeded
1279 area and seeding material to be added by plane, burner or rocket; (b) the
1280 intended outcome of the seeding in red, when the added large CCN form
1281 drops that grow via condensation and trigger collision and coalescence to
1282 form rain; the additional release of latent heat may invigorate the cloud.

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1285 Figure 3 (a) glaciogenic seeding of a convective cloud; in red: the seeded
1286 area and seeding material to be added by plane, burner or rocket; (b):
1287 the intended outcome of the seeding in red, when the added INP form
1288 crystals that grow via WBF and riming and melt below the 0°C isotherm;
1289 the additional release of latent heat may invigorate the cloud.

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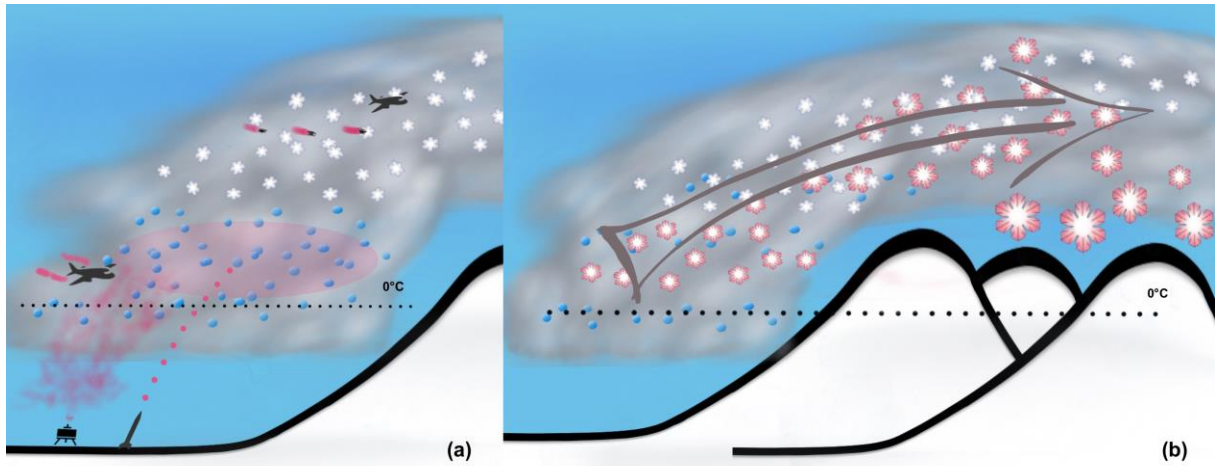
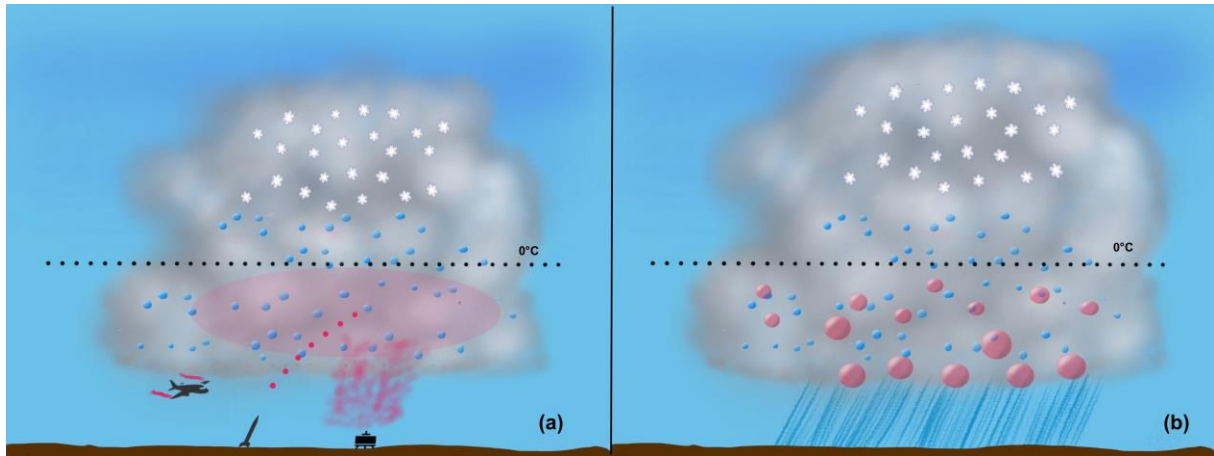


Figure 1 (a) glaciogenic seeding of an orographic winter time cloud; in red: the supercooled seeded area and the seeding material to be added by plane, burner or rocket; (b) the intended outcome of the seeding in red, when the added INP form crystals that grow via WBF effect and riming to form snow; the additional release of latent heat may invigorate the cloud; the arrow indicates the sense of the space and time evolution.

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Figure 2 (a) hygroscopic seeding of a convective cloud; in red: the seeded area and seeding material to be added by plane, burner or rocket; (b) the intended outcome of the seeding in red, when the added large CCN form drops that grow via condensation and trigger collision and coalescence to form rain; the additional release of latent heat may invigorate the cloud.

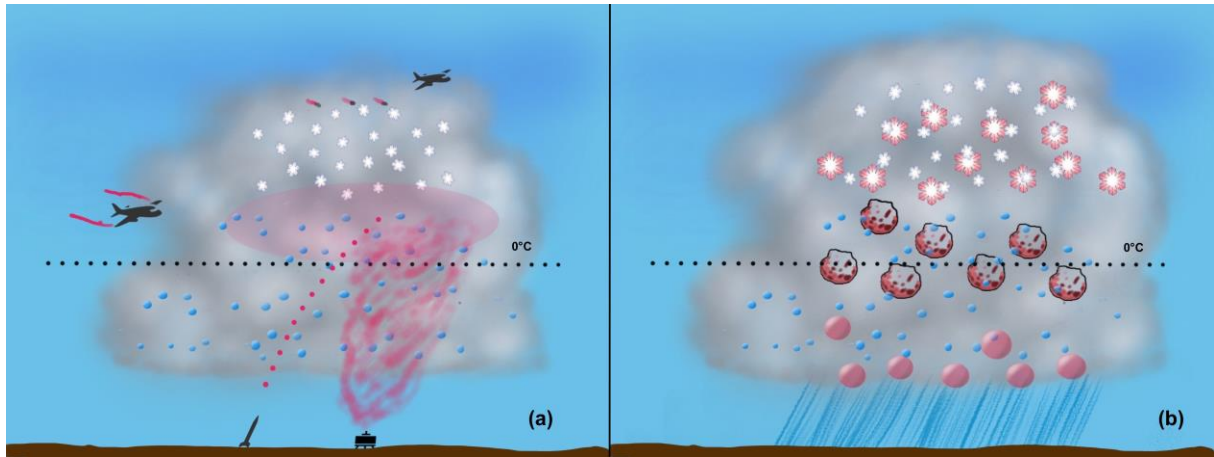


Figure 3 (a) glaciogenic seeding of a convective cloud; in red: the seeded area and seeding material to be added by plane, burner or rocket; (b): the intended outcome of the seeding in red, when the added INP form crystals that grow via WBF and riming and melt below the 0°C isotherm; the additional release of latent heat may invigorate the cloud.