



HAL
open science

Review of Advances in Precipitation Enhancement Research

Andrea I. Flossmann, Michael Manton, Ali Abshaev, Roelof Bruintjes,
Masataka Murakami, Thara Prabhakaran, Zhanyu Yao

► **To cite this version:**

Andrea I. Flossmann, Michael Manton, Ali Abshaev, Roelof Bruintjes, Masataka Murakami, et al..
Review of Advances in Precipitation Enhancement Research. Bulletin of the American Mathematical Society, In press, 10.1175/BAMS-D-18-0160.1 . hal-02125271

HAL Id: hal-02125271

<https://uca.hal.science/hal-02125271>

Submitted on 10 May 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Review of Advances in Precipitation Enhancement Research**

2

3 Andrea I. Flossmann⁽¹⁾ (Corresponding author), Michael Manton⁽²⁾, Ali

4 Abshaev⁽³⁾, Roelof Bruintjes⁽⁴⁾, Masataka Murakami⁽⁵⁾, Thara

5 Prabhakaran⁽⁶⁾, Zhanyu Yao⁽⁷⁾

6

7 (1) : Université Clermont Auvergne/CNRS/Laboratoire de Météorologie

8 Physique, Clermont-Ferrand, France

9 Email: andrea.flossmann@uca.fr

10

11 (2) School of Earth Atmosphere and Environment, Monash University,

12 Australia

13

14 (3) Hail Suppression Research Center, Nalchik, Russia

15

16 (4) National Center for Atmospheric Research, Boulder CO, USA

17

18 (5) Institute for Space-Earth Environment Research, Nagoya University,

19 Nagoya, Japan

20

21 (6) Indian Institute of Tropical Meteorology, Pune, India

22

23 (7) Chinese Academy of Meteorological Sciences, Beijing, China

24

25 **Abstract**

26

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

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

35

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

42

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

46

47

48

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

55 **1. Introduction**

56

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

72

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

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

87

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

98

99 **2. Natural cloud systems and their variability**

100

101 **2.1 Microphysics of clouds**

102

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.

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

131

132 Nucleated liquid cloud particles may grow to precipitation-sized drops
133 through condensation and then collision-coalescence processes. The
134 collision efficiency depends strongly on the difference between terminal
135 velocities of drops, and hence on the drop size distribution (Twomey,
136 1977). The transition from droplets to raindrops is efficient when
137 nucleation occurs on few CCN with a large variance in their sizes. On the
138 other hand, many small droplets with a narrow size distribution will often
139 be activated in a polluted environment, decreasing the likelihood of
140 collision and coalescence and resulting potentially in a reduction in the
141 efficiency of the transition to rain (e.g., Flossmann and Wobrock 2010).

142

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

149

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

160

161 2.2 **Dynamics of the cloud systems of interest in precipitation** 162 **enhancement**

163

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

174 The distribution of orographic precipitation is controlled by microphysical
175 processes, airflow dynamics, and moist-air thermodynamics (Houze
176 2012). Watson and Lane (2014) and Geerts et al. (2015) demonstrate
177 that orographic precipitation is sensitive to the terrain geometry (aspect
178 ratio) and the low-level stability of the flow (Froude number). Thus,
179 provided that any embedded convection is not too intense, the spatial and
180 temporal distribution of precipitation on the ground can be estimated with
181 some accuracy.

182

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

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

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

202

203 **3. Potential for precipitation enhancement**

204

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

209

210 **3.1 Winter orographic cloud systems**

211

212 Tessendorf et al. (2019) summarise the progress that has been made in
213 recent years on orographic cloud seeding. For wintertime orographic
214 clouds, precipitation is influenced by the local orography, with SLW being
215 generated as moist air near the freezing level rises over the ranges. The
216 basic hypothesis of orographic cloud seeding is that the introduction of
217 artificial INP (usually silver iodide, AgI) to the orographically-generated
218 SLW promotes the formation of ice particles at relatively warm (around -5
219 °C) temperatures, and that these particles subsequently grow by
220 deposition and collision leading to enhanced precipitation on the ground
221 over the ranges (see figure 1a and b for a schematic illustration). This

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

224 Geerts et al. (2010) follow the impact of ground-based seeding of AgI
225 particles on the microphysics of orographic clouds associated with the
226 Wyoming Weather Modification Pilot Project (WWMPP; Breed et al. 2014).

227 The seeding impact is identified by comparing the radar data from seeded
228 and unseeded flight legs using contoured frequency – altitude displays
229 (CFADs), developed by Yuter and Houze (1995). The impact of seeding
230 shown by the CFADs increases with Froude number, that is with
231 decreasing flow stability. Building on such studies, French et al. (2018)
232 provide a detailed record of the processes associated with the
233 enhancement of precipitation from wintertime orographic cloud systems
234 for the mountain ranges of south western Idaho, USA.

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

244

245 A third strategy for the injection of seeding material into cloud involves
246 various ground-based techniques. In addition to ground-based acetone
247 burners, artillery shells and rockets (including high-altitude fireworks)
248 have been used for cloud seeding (Abshaev et al. 2006). The challenge for
249 all ground-based techniques is to ensure that the INP reach the
250 appropriate cloud level for seeding. Remote sensing (Tessendorf et al.
251 2019) allows to follow the propagation of the seeded material in the cloud.
252 Observation and modelling studies (Bruitjes et al. 1995; Xue et al. 2013)
253 suggest that direct seeding strategies are more effective than ground-
254 based generators.

255

256 **3.2 Convective cloud systems**

257

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

266

267 *Hygroscopic seeding* particles tend to be salts with sizes in the range of
268 0.1-10 μm (e.g., Segal et al. 2004; Drofa et al. 2013), and they are

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

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

290

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

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

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

309

310 **4. Advances in observations**

311

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

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

318

319 **4.1 Precipitation on the ground**

320

321 Accurate observation of the natural precipitation and any artificial
322 enhancement is essential to precipitation enhancement research.

323 However, this remains a challenge due to the high spatial and temporal
324 variability of precipitation, especially in convective systems. Ground-based
325 precipitation gauges provide the most accurate measurements of
326 precipitation over a catchment-scale area. Villarini et al. (2008) confirm
327 that sampling errors for precipitation increase as the temporal integration
328 time decreases. The specified periods when seeding may occur in a cloud
329 seeding project are known as experimental units (EUs), and they can
330 currently be as short as a few hours (Manton et al. 2011; Breed et al.
331 2014). The uncertainties associated with precipitation measurements over
332 an EU duration need to be taken into account when evaluating cloud
333 seeding projects.

334

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

340 feasible at remote sites, and so understanding the uncertainties of sub-
341 optimal but practical techniques is essential. Indeed Kochendorfer et al.
342 (2018) use results from the World Meteorological Organization Solid
343 Precipitation Intercomparison Experiment (WMO-SPICE) to show that the
344 more effective the wind shield the more accurate are bias adjustments for
345 under-catch.

346

347 Scanning radars can be used to estimate precipitation over a large area,
348 especially where the terrain is steep and rough. While progress continues
349 to be made in reducing the uncertainties from radar reflectivity (e.g.,
350 Hasan et al. 2016), the application of dual-polarisation radar to
351 precipitation estimation has been a major development (Brandes et al.
352 2002), so that information on hydrometeor phase and shape can be used
353 when calibrating radars against local disdrometers.

354

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

363 are used together, especially for convective precipitation (Zhang et al.
364 2016).

365

366 **4.2 Synoptic environment**

367

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

377

378 **4.3 Cloud dynamics**

379

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

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

393

394 Radars are complemented by the recent generation of geostationary
395 satellites in providing information on cloud structure and microphysics to
396 support decision making and analysis in cloud seeding projects. These
397 satellites have spatial resolution of about 1 km, around 16 spectral
398 channels, and scanning intervals on the order of 10 minutes (Bessho et al.
399 2016; Schmit et al. 2017).

400

401 **4.4 Microphysics**

402

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

407

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

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

416

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

422

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

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

441

442 **5. Advances in modelling**

443

444 In recent years there has been significant progress in the modelling of
445 clouds. Ready access to models like the Weather Research and
446 Forecasting (WRF) Model (Liu et al. 2008) means that three-dimensional
447 mesoscale modelling of entire cloud systems embedded in a large-scale
448 flow is now standard practice. These models are driven by numerical
449 weather prediction (NWP) model output, with nesting capabilities that
450 support zooming into a region of interest at grid sizes approaching Large-
451 Eddy Simulation (LES) scales (Chu et al. 2017a; 2017b; Xue et al. 2016).
452 The models include multi-moment or bin-resolved microphysics schemes.
453 Model complexity can be further increased by combining the atmospheric
454 model results with snowpack, snowmelt and runoff models (Yoshida et al.
455 2009) to assess the impact of seeding on seasonal time scales.

456

457 **5.1 Modelling of Microphysics**

458

459 For precipitation enhancement research, the cloud microphysical
460 parameterization is critical as it greatly affects the accuracy of numerical
461 model seeding experiments. Various cloud microphysical
462 parameterizations are currently coupled to non-hydrostatic models
463 (NHMs). For bulk cloud microphysical parameterizations, hydrometeors
464 are separated into distinct categories and the size distribution of each
465 category is represented by an inverse exponential function or a gamma
466 function. The change in the total mass, total number and/or radar
467 reflectivity (single, double or third moment bulk schemes) of the particles
468 in each category is predicted (e.g., Khain et al. 2015; Lompar et al.
469 2017). More detailed approaches have been proposed by Saleeby and
470 Cotton (2004) or Morrison and Milbrandt (2015), e.g.

471
472 For bin spectral microphysical parameterizations, the change in
473 hydrometeor size distribution is simulated in detail: each category is
474 divided into several size ranges (bins), and the change in particle number
475 (single-moment scheme) or in particle number and mass (double-moment
476 scheme) is calculated for each bin of each category. Such models allow
477 explicit representation of the nucleation of water drops and ice particles
478 on an ambient aerosol population and more realistically simulate clouds
479 under differing pollution conditions (e.g. Planche et al. 2010). Moreover,
480 the nucleation of ice particles through different INP modes can now be
481 considered (Hiron and Flossmann 2015). Some bin microphysics models

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

484

485 An outstanding source of uncertainty in cloud models is the sensitivity of
486 the results to variations in microphysics parameterizations (Geresdi et al.
487 2017). Sensitivities are found for both bin microphysics (Khain et al.
488 2015) and bulk models (Morrison and Grabowski 2007). Model
489 intercomparison studies may help resolve these uncertainties, especially if
490 they are accompanied by detailed field observations that can validate the
491 simulated processes.

492

493 **5.2 Modelling of seeding**

494

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

501

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

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

508

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

528

529 **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

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

560

561 **6.1 Economic issues**

562

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

569

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

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

581

582 In estimating the economic benefit of cloud seeding, it is necessary to also
583 account both for the benefits of additional water over the seeded area and
584 for the total costs of a continuing operational project. Those costs include
585 actions needed to obviate any potential environmental risks (WMO
586 2018a).

587

588 **6.2 Preliminary studies**

589

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

598

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

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

608

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

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

621

622 **6.3 Randomised design**

623

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

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

631 A key challenge for catchment-scale projects is that the signal-to-noise
632 ratio is invariably very small. This difficulty arises because the natural
633 variability of precipitation is high (especially for short-term EUs), while the
634 average impact of seeding is relatively low (below 20%). The design of a
635 catchment-scale project therefore needs to include a randomisation
636 process to select which EUs are seeded and which are not seeded
637 (unseeded). As with medical trials, scientists involved with decision
638 making for the project should not be aware of the seeding sequence.

639 An important decision of the randomisation process is the specification of
640 the seeding ratio: the ratio of the number of seeded events to the number
641 of unseeded events. A seeding ratio larger than one leads to the range of
642 environmental conditions for unseeded EUs being smaller than for seeded
643 EUs, causing greater statistical uncertainty (Manton and Warren 2011).

644

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

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

659

660 **6.4 Seedability conditions**

661

662 Especially for short-duration EUs, it is essential to have well-defined
663 environmental conditions for starting an EU. For glaciogenic seeding,
664 these seeding criteria need to ensure that SLW is available, that seeding
665 material will disperse to the SLW, that ice particles nucleated by the
666 seeding material will grow sufficiently to ultimately fall into the target
667 area, that suitable conditions for seeding will persist for the duration of an
668 EU, and that material from a seeded EU will not contaminate a following
669 unseeded EU. Preliminary observational and modelling studies provide the
670 basis for the specification of the seedability conditions (e.g., Manton et al.
671 2011; Breed et al. 2014; Freud et al. 2015). Cloud seeding operations
672 should also be supported by model-based forecasts (Murakami et al.
673 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

698 observing periods (for example, the aircraft data of Miao and Geerts
699 (2013) showing changes in cloud microphysics due to seeding in some
700 EUs).

701

702 **7. Conclusions and recommendations**

703

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

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

714

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

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

730

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

743

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

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

759

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

765 Our knowledge of microphysical processes remains incomplete, especially
766 on the formation and growth of solid hydrometeors. In particular, the
767 basis of secondary ice multiplication processes in cloud is poorly
768 understood. The interactions between cloud microphysics and dynamics
769 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-)

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

797

798 **Acknowledgements**

799

800 The WMO Expert Team on Weather Modification acknowledges the support
801 provided by the National Center of Meteorology, Abu Dhabi, UAE under
802 the UAE Research Program for Rain Enhancement Science.

803

804

805 **References**

806

807 Abshaev, M.T., A.M. Abshaev, G.K. Sulakvelidze, I.I. Burtsev and A.M.
808 Malkarova, 2006: Development of rocket and artillery technology for
809 hail suppression. *Achievements in Weather Modification*, Department
810 of Atmospheric Science, Abu Dhabi, 109-127.

811 Abshaev, M.T., A.M. Abshaev, A.M. Malkarova and M.V. Zharashuev,
812 2010: Automated radar identification, measurement of parameters,
813 and classification of convective cells for hail protection and storm
814 warning. *Russian Meteorology and Hydrology*, 35(3):182-189. DOI:
815 <https://doi.org/10.3103/S1068373910030040>

816 Abshaev M.T., A.M. Abshaev, M.V. Berekova and A.M. Malkarova, 2014:
817 *Manual on organization and execution of hail suppression projects,*
818 Nalchik, 508 pages.

819 Adzhiev A.K., R.K. Kalov, 2015: Studying the influence of electric charges
820 and fields on the efficiency of ice formation with silver iodide
821 particles, Collected papers "Problems of cloud physics" in the memory
822 of N.O. Plaude, Russian Hydrometeorological Service, Central
823 Aerological Observatory, Moscow, p. 73-88, ISBN: 978-5-901579-62-
824 6.

825 Araki, K., M. Murakami, H. Ishimoto and T. Tajiri, 2015: Ground-based
826 microwave radiometer variational analysis during no-rain and rain
827 conditions. *SOLA*, 11:108-112. DOI:
828 <https://doi.org/10.2151/sola.2015-026>

829 Baumgardner, D., S.J. Abel, D. Axisa, R. Cotton, J. Crosier, P. Field, C.
830 Gurganus, A. Heymsfield, A. Korolev, M. Krämer, P. Lawson, G.
831 McFarquhar, Z. Ulanowski and J. Um, 2017: Cloud ice properties: In
832 situ measurement challenges. *Meteorological monographs*, 58:9.1-
833 9.23.
834 DOI: <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0011.1>

835 Bessho, K., K. Date, M. Hayashi. A. Ikeda, T. Imai, H. Inoue, Y. Kumagai,
836 T. Miyakawa, H. Murata, T. Ohno, A. Okuyama, R. Oyama, Y. Sasaki,
837 Y. Shimazu, K. Shimoji and Y. Sumida, 2016: An introduction to

838 Himawari-8/9 - Japan's new-generation geostationary meteorological
839 satellites. *Journal of the Meteorological Society of Japan*, 94, 151-
840 183.

841 Brandes, E.A., G. Zhang and J. Vivekanandan, 2002: Experiments in
842 rainfall estimation with a polarimetric radar in a subtropical
843 environment. *Journal of Applied Meteorology and Climatology*,
844 41(6):674-685.
845 DOI: [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0450(2002)041<0674:EIREWA>2.0.CO;2)
846 [0450\(2002\)041<0674:EIREWA>2.0.CO;2](https://doi.org/10.1175/1520-0450(2002)041<0674:EIREWA>2.0.CO;2)

847 Breed, D., R. Rasmussen, C. Weeks, B. Boe and T. Deshler, 2014:
848 Evaluating winter orographic cloud seeding: Design of the Wyoming
849 Weather Modification Pilot Project (WWMPP). *Journal of Applied*
850 *Meteorology and Climatology*, 53(2):282-299. DOI:
851 <https://doi.org/10.1175/JAMC-D-13-0128.1>

852 Brintjes, R. T., Clark, T. L., Hall, W. D., 1995: The dispersion of tracer
853 plumes in mountainous regions in central Arizona: Comparisons
854 between observations and modeling results. *Journal of Applied*
855 *Meteorology*, 34(4), 971-988.

856 Brintjes, R.T., V. Salazar, T.A. Semeniuk, P. Buseck, D.W. Breed and J.
857 Gunkelman, 2012: Evaluation of hygroscopic cloud seeding flares.
858 *The Journal of Weather Modification*, 44(1):69-94. DOI:

859 <http://www.weathermodification.org/~weatherm/publications/index.p>
860 [hp/JWM/article/view/85](http://www.weathermodification.org/~weatherm/publications/index.php/JWM/article/view/85)

861 Chu, X., B. Geerts, L. Xue and B. Pokharel, 2017a: A case study of cloud
862 radar observations and large eddy simulations of a shallow stratiform
863 orographic cloud, and the impact of glaciogenic seeding. *Journal of*
864 *Applied Meteorology and Climatology*, 56:1285-1304. DOI:
865 <https://doi.org/10.1175/JAMC-D-16-0364.1>

866 Chu, X., B. Geerts, L. Xue and R. Rasmussen, 2017b: Large eddy
867 simulations of the impact of ground-based glaciogenic seeding on
868 shallow orographic convection: A case study. *Journal of Applied*
869 *Meteorology and Climatology*, 56:69-84.
870 DOI: <https://doi.org/10.1175/JAMC-D-16-0191.1>

871 Delanoë, J., A. Protat, J.-P. Vinson, W. Brett, C. Caudoux, F. Bertrand, J.P.
872 du Chatelet,
873 R. Hallali, L. Barthes, M. Haeffelin and J.-C. Dupont, 2016: BASTA: A
874 95-GHz FMCW Doppler radar for cloud and fog studies. *Journal of*
875 *Atmospheric and Oceanic Technology*, 33(5):1023-1038. DOI:
876 <https://doi.org/10.1175/JTECH-D-15-0104.1>

877 Dessens, J., J.L. Sánchez, C. Berthet, L. Hermida and A. Merino, 2016:
878 Hail prevention by ground-based silver iodide generators: Results of
879 historical and modern field projects. *Atmospheric Research*, 170:98-
880 111. DOI: <https://doi.org/10.1016/j.atmosres.2015.11.008>

881 Dixon, M. and G. Wiener, 1993: TITAN: Thunderstorm Identification,
882 Tracking, Analysis, and Nowcasting - A radar-based methodology.
883 *Journal of Atmospheric and Oceanic Technology*, 10(6):785-797.
884 DOI: [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0426(1993)010<0785:TTITAA>2.0.CO;2)
885 [0426\(1993\)010<0785:TTITAA>2.0.CO;2](https://doi.org/10.1175/1520-0426(1993)010<0785:TTITAA>2.0.CO;2)

886 Drofa, A.S., V.G. Eran'kov, V.N. Ivanov, A.G. Shilin and G.F. Iskevich,
887 2013: Experimental investigations of the effect of cloud-medium
888 modification by salt powders. *Izvestiya, Atmospheric and Oceanic*
889 *Physics*, 49(3):298-306.
890 DOI: <https://doi.org/10.1134/S0001433813030043>

891 Field, P.R., R.P. Lawson, P.R.A. Brown, G. Lloyd, C. Westbrook, D.
892 Moisseev, A. Miltenberger, A. Nenes, A. Blyth, T. Choulaton, P.
893 Connolly, J. Buehl, J. Crosier, Z. Cui, C. Dearden, P. DeMott, A.
894 Flossmann, A. Heymsfield, Y. Huang, H. Kalesse, Z.A. Kanji, A.
895 Korolev, A. Kirchgaessner, S. Lasher-Trapp, T. Leisner, G.
896 McFarquhar, V. Phillips, J. Stith and S. Sullivan, 2017: Secondary ice
897 production: Current state of the science and recommendations for the
898 future. *Meteorological Monographs*, 58:7.1-7.20

899 Fleming, J.R., 2010: "Fixing the Sky". *Columbia University Press*, pp 801.

900 Flossmann, A.I. and W. Wobrock, 2010: A review of our understanding of
901 the aerosol - cloud interaction from the perspective of a bin resolved

902 cloud scale modelling. *Atmospheric Research*, 97(4):478-497. DOI:
903 <https://doi.org/10.1016/j.atmosres.2010.05.008>

904 French J.R., K. Friedrich, S.A. Tessendorf, R.M. Rauber, B. Geerts, R.M.
905 Rasmussen, L. Xue, M.L. Kunkel and D.R. Blestrud, 2018:
906 Precipitation formation from orographic cloud seeding. Proceedings
907 of the National Academy of Sciences of the United States of
908 America, 201716995; published ahead of print January 22, 2018.
909 <https://doi.org/10.1073/pnas.1716995115>

910 Freud, E., H. Koussevitzky, T. Goren and D. Rosenfeld, 2015: Cloud
911 microphysical background for the Israel-4 cloud seeding experiment.
912 *Atmospheric Research*, 158-159:122-138. DOI:
913 <https://doi.org/10.1016/j.atmosres.2015.02.007>

914 Geerts, B., Q. Miao, Y. Yang, R. Rasmussen and D. Breed, 2010: An
915 airborne profiling radar study of the impact of glaciogenic cloud
916 seeding on snowfall from winter orographic clouds. *Journal of the*
917 *Atmospheric Sciences*, 67(10):3286-3302. DOI:
918 <https://doi.org/10.1175/2010JAS3496.1>

919 Geerts, B., Y. Yang, R. Rasmussen, S. Haimov and B. Pokharel, 2015:
920 Snow growth and transport patterns in orographic storms as
921 estimated from airborne vertical-plane dual- doppler radar data.
922 *Monthly Weather Review*, 143(2):644-665.
923 DOI: <https://doi.org/10.1175/MWR-D-14-00199.1>

924 Geresdi, I., L. Xue and R. Rasmussen, 2017: Evaluation of orographic
925 cloud seeding using a bin microphysics scheme: Two-dimensional
926 approach. *Journal of Applied Meteorology and Climatology*,
927 56(5):1443-1462. DOI: <https://doi.org/10.1175/JAMC-D-16-0045.1>

928 Ghosh, S., A. Sharma, S. Arora and G. Desouza, 2016: A geoengineering
929 approach toward tackling tropical cyclones over the Bay of Bengal,
930 *Atmospheric Science Letters*, 17, 208-215. DOI: 10.1002/asl.644

931 Grabowski, W.W., 2015: Untangling microphysical impacts on deep
932 convection applying a novel modeling methodology. *Journal of*
933 *Atmospheric Sciences*, 72, 2446-2464. [https://doi.org/10.1175/JAS-](https://doi.org/10.1175/JAS-D-14-0307.1)
934 [D-14-0307.1](https://doi.org/10.1175/JAS-D-14-0307.1)

935 Hasan, M.M., A. Sharma, G. Mariethoz, F. Johnson and A. Seed, 2016:
936 Improving radar rainfall estimation by merging point rainfall
937 measurements within a model combination framework. *Advances in*
938 *Water Resources*, 97:205-218.
939 DOI: <https://doi.org/10.1016/j.advwatres.2016.09.011>

940 Hashimoto, A., N. Orikasa, T. Tajiri, and M. Murakami, 2017: Numerical
941 prediction experiment over the United Arab Emirates by using JMA-
942 NHM. CAS/JSC WGNE Research Activities in Atmospheric and Oceanic
943 Modelling 47, 5-07

944 Hiron, T. and A. I. Flossmann, 2015: A study of the role of the
945 parameterization of heterogeneous ice nucleation for the modeling of

946 microphysics and precipitation of a convective cloud. *Journal of the*
947 *Atmospheric Sciences*, 72:3322–3339.
948 DOI: <http://dx.doi.org/10.1175/JAS-D-15-0026.1>

949 Hoose, C. and O. Möhler, 2012: Heterogeneous ice nucleation on
950 atmospheric aerosols: A review of results from laboratory
951 experiments. *Atmospheric Chemistry and Physics*, 12(20):9817-9854.
952 DOI: <https://doi.org/10.5194/acp-12-9817-2012>

953 Houze Jr., R.A., 2012: Orographic effects on precipitating clouds. *Reviews*
954 *of Geophysics*, 50(1):1-47. DOI:
955 <http://dx.doi.org/10.1029/2011RG000365>

956 Kanji Z.A., L.A. Ladino, H. Wex, Y. Boose, M. Burkert-Kohn, D.J. Cziczo
957 and M. Krämer, 2017: Overview of ice nucleating particles.
958 *Meteorological Monographs*, 58:1.1-1.33. DOI:
959 <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0006.1>

960

961 Khain, A. P., K. D. Beheng, A. Heymsfield, A. Korolev, S. O. Krichak, Z.
962 Levin, M. Pinsky, V. Phillips, T. Prabhakaran, A. Teller, et al. (2015),
963 Representation of microphysical processes in cloud-resolving models:
964 Spectral (bin) microphysics versus bulk parameterization, *Review of*
965 *Geophysics.*, 53, 247–322. doi:10.1002/2014RG000468.
966

967 Kochendorfer, J., R. Nitu, M. Wolff, E. Mekis, R. Rasmussen, B. Baker,
968 M.E. Earle, A. Reverdin, K. Wong, C.D. Smith, D. Yang, Y.A. Roulet,
969 T. Meyers, S. Buisan, K. isaksen, R. Braekkan, S. landolt and A.
970 Jachisl, 2018: Testing and development of transfer functions for
971 weighing precipitation gauges in WMO-SPICE. *Hydrol. Earth. Syst.*
972 *Sci.*, 22: 1437-1452.

973 Koshida, T., M. Murakami, K. Yoshida, F. Fujibe and K. Takahashi, 2012:
974 Assessment of Clouds Suitable for Summertime Precipitation
975 Augmentation over Shikoku Island. *SOLA*, 8, 160-164,
976 DOI:10.2151/sola.2012-039.

977 Krajewski W.F., G. Villarini and J.A. Smith, 2010: Radar-rainfall
978 uncertainties: Where are we after thirty years of effort? *Bulletin of*
979 *the American Meteorological Society*, 91, 87-94.

980 Kuba, N. and M. Murakami, 2010: Effect of hygroscopic seeding on warm
981 rain clouds - numerical study using a hybrid cloud microphysical
982 model. *Atmospheric Chemistry and Physics*, 10:3335-3351. DOI:
983 [https://www.atmos-chem-](https://www.atmos-chem-phys.net/10/3335/2010/acp-10-3335-2010.pdf)
984 [hys.net/10/3335/2010/acp-10-3335-](https://www.atmos-chem-phys.net/10/3335/2010/acp-10-3335-2010.pdf)
2010.pdf

985 Kulkarni, J.R., R.S. Maheskumar, S.B. Morwal, B.P. Kumari, M. Konwar,
986 C.G. Deshpande, R.R. Joshi, R.V. Bhalwankar, G. Pandithurai, P.D.
987 Safai, S.G. Narkhedkar, K.K. Dani, A. Nath, S. Nair, V.V. Sapre, P.V.
988 Puranik, S.S. Kandalgaonkar, V.R. Mujumdar, R.M. Khaladkar, R.

989 Vijayakumar, T.V. Prabha and B.N. Goswami, 2012: The Cloud
990 Aerosol Interaction and Precipitation Enhancement Experiment
991 (CAIPEEX): Overview and preliminary results. *Current Science*,
992 102(3)413-425. DOI: <http://repository.ias.ac.in/93580/1/7-p.pdf>

993 Kurdzo, J.M., F. Nai, D.J. Bodine, T.A. Bonin, R.D. Palmer, B.L. Cheong, J.
994 Lujan, A. Mahre and A.D. Byrd, 2017: Observations of severe local
995 storms and tornadoes with the atmospheric imaging radar. *Bulletin of*
996 *the American Meteorological Society*, 98(5): 915-935. DOI:
997 <https://doi.org/10.1175/BAMS-D-15-00266.1>

998 Lawson, R.P., S. Woods and H. Morrison, 2015: The microphysics of ice
999 and precipitation development in tropical cumulus clouds. *Journal of*
1000 *the Atmospheric Science*, 72(6):2429-2445. DOI:
1001 <https://doi.org/10.1175/JAS-D-14-0274.1>

1002 Leisner, T., D. Duft, O. Möhler, H. Saathoff, M. Schnaiter, S. Henin, K.
1003 Stelmaszczyk, M. Petrarca, R. Delagrange, Z. Hao, J. Lüder, Y. Petit,
1004 P. Rohwetter, J. Kasparian, J.-P. Wolf and L. Wöste, 2013: Laser-
1005 induced plasma cloud interaction and ice multiplication under cirrus
1006 cloud conditions. *Proceedings of the National Academy of Sciences of*
1007 *the United States of America*, 110 (25) 10106-10110.
1008 <https://doi.org/10.1073/pnas.1222190110>

1009 Liu, Y., T.T. Warner, J.F. Bowers, L.P. Carson, F. Chen, C.A. Clough, C.A
1010 Davis, C.H. Egeland, S.F. Halvorson, T.W. Huck Jr., L. Lachapelle,

1011 R.E. Malone, D.L. Rife, R.-S. Sheu, S.P. Swerdlin and D.S.
1012 Weingarten, 2008: The operational mesogamma-scale analysis and
1013 forecast system of the U.S. Army test and evaluation command. Part
1014 I: Overview of the modeling system, the forecast product, and how
1015 the products are used. *Journal of Applied Meteorology and*
1016 *Climatology*, 47(4):1077-1092. DOI:
1017 <https://doi.org/10.1175/2007JAMC1653.1>

1018 Lompar, M., M. Ćurić and D. Romanic, 2017: Simulation of a severe
1019 convective storm using a numerical model with explicitly incorporated
1020 aerosols. *Atmospheric Research*, 194, 164-177.
1021 <https://doi.org/10.1016/j.atmosres.2017.04.037>

1022 Maahn, M. and P. Kollias, 2012: Improved micro rain radar snow
1023 measurements using Doppler spectra post-processing. *Atmospheric*
1024 *Measurements Techniques*, 5(11):2661-2673. DOI:
1025 <https://doi.org/10.5194/amt-5-2661-2012>

1026 Manton, M.J., L. Warren, S.L. Kenyon, A.D. Peace, S.P. Bilish and K.
1027 Kemsley, 2011: A confirmatory snowfall enhancement project in the
1028 snowy mountains of Australia. Part I: Project design and response
1029 variables. *Journal of Applied Meteorology and Climatology*,
1030 50(7):1432-1447. DOI: <https://doi.org/10.1175/2011JAMC2659.1>

1031 Manton, M.J. and L. Warren, 2011: A confirmatory snowfall enhancement
1032 project in the snowy mountains of Australia. Part II: Primary and

1033 associated analyses. *Journal of Applied Meteorology and Climatology*,
1034 50(7):1448-1458.
1035 DOI: <https://doi.org/10.1175/2011JAMC2660.1>

1036 Manton, M.J., A.D. Peace, K. Kemsley, S. Kenyon, J.C. Speirs, L. Warren
1037 and J. Denholm, 2017: Further analysis of a snowfall enhancement
1038 project in the snowy mountains of Australia. *Atmospheric Research*,
1039 193:192-203.
1040 DOI: <https://doi.org/10.1016/j.atmosres.2017.04.011>

1041 McFarquhar, G.M., D. Baumgardner, A. Bansemer, S.J. Abel, J. Crosier, J.
1042 French, P. Rosenberg, A. Korolev, A. Schwarzenboeck, D. Leroy, J.
1043 Um, W. Wu, A.J. Heymsfield, C. Twohy, A. Detwiler, P. Field, A.
1044 Neumann, R. Cotton, D. Axisa and J. Dong, 2017: Processing of ice
1045 cloud in situ data collected by bulk water, scattering, and imaging
1046 probes: Fundamentals, uncertainties, and efforts toward consistency.
1047 *Meteorological Monographs*, 58:11.1-11.33.
1048 DOI: <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0007.1>

1049 Miao, Q. and B. Geerts, 2013: Airborne measurements of the impact of
1050 ground-based glaciogenic cloud seeding on orographic precipitation.
1051 *Advances in Atmospheric Sciences*, 30(4)1025-1038.

1052 Morrison, H. and W. W. Grabowski, 2007: Comparison of Bulk and Bin
1053 Warm-Rain Microphysics Models Using a Kinematic Framework. *J.*
1054 *Atmos. Sci.*, 64 (2007), 2839-2861, 10.1175/JAS3980

1055 Morrison, H. and J.A. Milbrandt, 2015: Parameterization of cloud
1056 microphysics based on the prediction of bulk ice particle properties.
1057 Part I: Scheme description and idealized tests. *Journal of the*
1058 *Atmospheric Sciences*, 72:287-311.
1059 DOI: <https://doi.org/10.1175/JAS-D-14-0065.1>

1060 Murakami, M. and JCSEPA research group, 2011: Japanese Cloud Seeding
1061 Experiments for Precipitation Augmentation (JCSEPA) –New
1062 approaches and some results from wintertime and summertime
1063 weather modification programs. Proceedings of 10th WMO Scientific
1064 Conference on Weather Modification, Bali, Indonesia, 4-7 October
1065 2011.
1066 [https://www.wmo.int/pages/prog/arep/wwrp/new/documents/OBS.M](https://www.wmo.int/pages/prog/arep/wwrp/new/documents/OBS.Murakami_Japan.pdf)
1067 [urakami_Japan.pdf](https://www.wmo.int/pages/prog/arep/wwrp/new/documents/OBS.Murakami_Japan.pdf)

1068 National Research Council, 2003: Critical issues in weather modification
1069 research. *National Academy Press*, USA. 131 pp.

1070 Osburn, L., T. Chubb, S. Siems, M. Manton and A.D. Peace, 2016:
1071 Observations of supercooled liquid water in wintertime alpine storms
1072 in south east Australia. *Atmospheric Research*, 169, 345-356.

1073 Planche, C., W. Wobrock, A.I. Flossmann, F. Tridon, J. Van Baelen, Y.
1074 Pointin and M. Hagen, 2010: The influence of aerosol particle number
1075 and hygroscopicity on the evolution of convective cloud systems and
1076 their precipitation: A numerical study based on the COPS

1077 observations on 12 August 2007. *Atmospheric Research*, 98(1):40-
1078 56. DOI: <https://doi.org/10.1016/j.atmosres.2010.05.003>

1079 Pokharel, B., B. Geerts, X. Jing, K. Friedrich, J. Aikins, D. Breed, R.
1080 Rasmussen and A. Huggins, 2014: The impact of ground-based
1081 glaciogenic seeding on clouds and precipitation over mountains: A
1082 multi-sensor case study of shallow precipitating orographic cumuli.
1083 *Atmospheric Research*, 147-148:162-182.
1084 DOI: <https://doi.org/10.1016/j.atmosres.2014.05.014>

1085 Popov, V.B., and A.A. Sinkevich, 2017: Investigation of Cu Murger in the
1086 North-West of Russia, Trudy MGO, v, 585 p. 39-55.
1087

1088 Prabha, T.V., A. Khain, R.S. Maheshkumar, G. Pandithurai, J.R. Kulkarni,
1089 M. Konwar and B.N. Goswami, 2011: Microphysics of premonsoon
1090 and monsoon clouds as seen from in situ measurements during the
1091 Cloud Aerosol Interaction and Precipitation Enhancement Experiment
1092 (CAIPEEX). *Journal of the Atmospheric Sciences*, 68(9):1882-
1093 1901. DOI: <https://doi.org/10.1175/2011JAS3707.1>

1094 Pruppacher, H.R. and J.D. Klett, 1997: *Microphysics of Clouds and*
1095 *Precipitation: With an Introduction to Cloud Chemistry and Cloud*
1096 *Electricity*, 2nd ed., Atmospheric and Oceanographic Sciences Library,
1097 *Kluwer Academic Publishers*. 954 pp.

1098 Rasmussen, R., B. Baker, J. Kochendorfer, T. Meyers, S. Landolt, A.P.
1099 Fischer, J. Black, J.M. Thériault, P. Kucera, D. Gochis, C. Smith, R.
1100 Nitu, M. Hall, K. Ikeda and E. Gutmann, 2012: How well are we
1101 measuring snow: The NOAA/FAA/NCAR winter precipitation test bed.
1102 *Bulletin of the American Meteorological Society*, 93(6):811-829. DOI:
1103 <https://doi.org/10.1175/BAMS-D-11-00052.1>

1104 Rasmussen, R.M., S. Tessendorf, L. Xue, C. Weeks, K. Ikeda, S. Landolt,
1105 D. Breed, T. Deshler, B. Lawrence, 2018: Evaluation of the Wyoming
1106 Weather Modification Pilot Project (WWMPP) using two approaches:
1107 traditional statistics and ensemble modeling. *J. Appl. Meteor.*
1108 *Climatol.*, 57: 2639-2660. [https://doi.org/10.1175/JAMC-D-17-](https://doi.org/10.1175/JAMC-D-17-0335.1)
1109 [0335.1](https://doi.org/10.1175/JAMC-D-17-0335.1)

1110 Ritzman, J.M., T. Deshler, K. Ikeda and R. Rasmussen, 2015: Estimating
1111 the fraction of winter orographic precipitation produced under
1112 conditions meeting the seeding criteria for the Wyoming weather
1113 Modification Pilot Project. *Journal of Applied Meteorology and*
1114 *Climatology*, 54:1202-1215. DOI: [https://doi.org/10.1175/JAMC-D-](https://doi.org/10.1175/JAMC-D-14-0163.1)
1115 [14-0163.1](https://doi.org/10.1175/JAMC-D-14-0163.1)

1116 Ryan, B.F., and W.D. King, 1997: A critical review of the Australian
1117 experience in cloud seeding. *Bull. Americ. Meteorol. Soc.*, 78, 239–
1118 254.

1119 Saleeby, S.M. and W.R. Cotton, 2004: A large-droplet mode and
1120 prognostic number concentration of cloud droplets in the Colorado
1121 State University Regional Atmospheric Modeling System (RAMS). Part
1122 I: Module descriptions and supercell test simulations. *Journal of*
1123 *Applied Meteorology and Climatology*, 43:182-195. DOI:
1124 [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0450(2004)043<0182:ALMAPN>2.0.CO;2)
1125 [0450\(2004\)043<0182:ALMAPN>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<0182:ALMAPN>2.0.CO;2)

1126 Schmit, T.J., P. Griffith, M.M. Gunshor, J.M. Daniels, S.J. Goodman and
1127 W.J. Lebar, 2017: A closer look at the ABI on the GOES-R series.
1128 *Bulletin of the American Meteorological Society*, 98(4):681-698. DOI:
1129 <https://doi.org/10.1175/BAMS-D-15-00230.1>

1130 Segal, Y., A. Khain, M. Pinsky and D. Rosenfeld, 2004: Effects of
1131 hygroscopic seeding on raindrop formation as seen from simulations
1132 using a 2000-bin spectral cloud parcel model. *Atmospheric Research*,
1133 71(1):3-34.
1134 DOI: <https://doi.org/10.1016/j.atmosres.2004.03.003>

1135 Segal, Y., M. Pinsky, and A. Khain, 2007: The role of competition effect in
1136 the raindrop formation. *Atmospheric Research*, 83, 106–118.

1137 Seto, J., K. Tomine, K. Wakimizu and K. Nishiyama, 2011: Artificial cloud
1138 seeding using liquid carbon dioxide: Comparison of experimental data
1139 and numerical analyses. *Journal of Applied Meteorology and*

1140 Climatology, 50(7):1417-1431. DOI:
1141 <https://doi.org/10.1175/2011JAMC2592.1>

1142 Shippey, K., A. Gørgens, D. Terblanche and M. Luger, 2004:
1143 Environmental challenges to operationalisation of South African
1144 rainfall enhancement. *Water SA*, Vol. 30 No. 5; 88-92,
1145 <http://www.wrc.org.za>

1146 Silverman, B.A. and W. Sukarnjanaset, 2000: Result of the Thailand
1147 warm-cloud hygroscopic particle seeding experiment. *Journal of*
1148 *Applied Meteorology and Climatology*, 39(7):1160-1175.
1149 DOI: <https://doi.org/10.1175/1520->
1150 [0450\(2000\)039<1160:ROTTWC>2.0.CO;2](https://doi.org/10.1175/1520-0450(2000)039<1160:ROTTWC>2.0.CO;2)

1151 Tai, Y., H. Liang, A. Zaki, N. El Hadri, A.M. Abshaev, B.M. Huchinaev, S.
1152 Griffiths, M. Jouiad, and L. Zou, 2017: Core/shell microstructure
1153 induced synergistic effect for efficient water-droplet formation and
1154 cloud-seeding application. *ACS Nano*, 11(12):12318- 12325. DOI:
1155 <http://pubs.acs.org/doi/abs/10.1021/acsnano.7b06114>

1156 Tan, X., Y. Qiu, Y. Yang, D. Liu, X. Lu and Y. Pan, 2016: Enhanced growth
1157 of single droplet by control of equivalent charge on droplet. *IEEE*
1158 *Transactions on Plasma Science*, 44 (11), 2724-2728.

1159 Terblanche, D.E., F.E. Steffens, L. Fletcher, M.P. Mittermaier and R.C.
1160 Parsons, 2000: Toward the operational application of hygroscopic
1161 flares for rainfall enhancement in South Africa. *Journal of Applied*

1162 *Meteorology and Climatology*, 39(11):1811-1821.
1163 DOI: <https://doi.org/10.1175/1520->
1164 [0450\(2001\)039<1811:TTOAOH>2.0.CO;2](https://doi.org/10.1175/1520-0450(2001)039<1811:TTOAOH>2.0.CO;2)

1165 Terblanche, D.E., M.P. Mittermaier, R.P. Burger, K.J.P. De Waal and X.G.
1166 Ncipha, 2005: The South African rainfall enhancement programme:
1167 1997-2001. *Water SA*, 31(3):291-298. DOI:
1168 <http://hdl.handle.net/10520/EJC116273>

1169 Tessendorf, S.A., R.T. Brintjes, C. Weeks, J.W. Wilson, C.A. Knight, R.D.
1170 Roberts, J.R. Peter, S. Collis, P.R. Buseck, E. Freney, M. Dixon, M.
1171 Pocernich, K. Ikeda, D. Axisa, E. Nelson, P.T. May, H. Richter, S.
1172 Piketh, R.P. Burger, L. Wilson, S.T. Siems, M. Manton, R.C. Stone, A.
1173 Pepler, D.R. Collins, V.N. Bringi, M. Thurai, L. Turner and D. McRae,
1174 2012: The Queensland cloud seeding research program. *Bulletin of*
1175 *the American Meteorological Society*, 93, 74-90.

1176 Tessendorf, S., J. R. French, K. Friedrich, B. Geerts, R. M. Rauber, R. M.
1177 Rasmussen, L. Xue, and K. Ikeda, D. R. Blestrud, M. L. Kunkel, and
1178 S. Parkinson, J. R. Snider, J. Aikins, S. Faber, A. Majewski, C.
1179 Grasmick, and P. T. Bergmaier, A. Janiszewski, A. Springer, C. Weeks,
1180 D. J. Serke, and R. Brintjes, 2019: Transformational approach to
1181 winterorographic weather modification research: The
1182 SNOWIEProject., *Bull. Amer. Meteor. Soc.*, 71-92,
1183 <https://doi.org/10.1175/BAMS-D-17-0152.1>

1184 Twomey, S., 1977: The influence of pollution on the shortwave albedo of
1185 clouds. *Journal of the Atmospheric Sciences*, 34(7):1149-1152. DOI:
1186 [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2)
1187 [0469\(1977\)034<1149:TIOPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2)

1188 Vali, G., P.J. DeMott, O. Mohler and T.F. Whale, 2015: Technical Note: A
1189 proposal for ice nucleation terminology. *Atmospheric Chemistry and*
1190 *Physics*, 15, 10263-10270. [http://www.atmos-chem-](http://www.atmos-chem-phys.net/15/10263/2015/)
1191 [phys.net/15/10263/2015/](http://www.atmos-chem-phys.net/15/10263/2015/)

1192 Villarini, G., P.V. Mandapaka, W.F. Krajewski and R.J. Moore, 2008:
1193 Rainfall and sampling uncertainties: A rain gauge perspective. *Journal*
1194 *of Geophysical Research: Atmospheres*, 113(D11). DOI:
1195 <http://dx.doi.org/10.1029/2007JD009214>

1196 Watson, C.D. and T.P. Lane, 2014: Further sensitivities of orographic
1197 precipitation to terrain geometry in idealized simulations. *Journal of*
1198 *the Atmospheric Sciences*, 71:3068-3089. DOI:
1199 <https://doi.org/10.1175/JAS-D-13-0318.1>

1200 Wang, Z., J. French, G. Vali, P. Wechsler, S. Haimov, A. Rodi, M. Deng, D.
1201 Leon, J. Sinder, L. Peng and A.L. Pazmany, 2012: Single aircraft
1202 integration of remote sensing and in situ sampling for the study of
1203 cloud microphysics and dynamics. *Bulletin of the American*
1204 *Meteorological Society*, 93(5):653-668. DOI:
1205 <https://doi.org/10.1175/BAMS-D-11-00044.1>

1206 Wieringa, J. and I. Holleman, 2006: If cannons cannot fight hail, what
1207 else? *Meteorologische Zeitschrift*, 15(6):659-669, DOI:
1208 <https://doi.org/10.1127/0941-2948/2006/0147>

1209 World Meteorological Organization, 2000: *Report on the WMO*
1210 *International Workshop on Hygroscopic Seeding: experimental*
1211 *results, physical processes, and research needs*. WMO Report No. 35,
1212 WMO/TD No. 1006, 68 pp. Geneva, Switzerland.

1213 World Meteorological Organization, 2010: WMO DOCUMENTS ON
1214 WEATHER MODIFICATION; Updated in the meeting of the Expert
1215 Team on Weather Modification Research; Abu Dhabi, 22-24 March
1216 2010;
1217 http://www.wmo.int/pages/prog/arep//wwrp/new/documents/WMR_
1218 [documents.final_27_April_1.FINAL.pdf](http://www.wmo.int/pages/prog/arep//wwrp/new/documents/WMR_documents.final_27_April_1.FINAL.pdf)

1219 World Meteorological Organization, 2018a: Peer Review Report on Global
1220 Precipitation Enhancement Activities; WWRP 2018 – 1;
1221 http://www.wmo.int/pages/prog/arep/wwrp/new/documents/FINAL_
1222 [WWRP_2018_1.pdf](http://www.wmo.int/pages/prog/arep/wwrp/new/documents/FINAL_WWRP_2018_1.pdf)

1223

1224 World Meteorological Organization, 2018b: Plans and Guidance for
1225 weather Modification Activities in: Executive Council - Sixty-ninth
1226 session: Abridged final report with resolutions and decisions;
1227 https://library.wmo.int/doc_num.php?explnum_id=3645
1228

1229 Xue, L., S.A. Tessendorf, E. Nelson, R. Rasmussen, D. Breed, S.
1230 Parkinson, P. Holbrook and D. Blestrud, 2013: Implementation of a
1231 silver iodide cloud-seeding parameterization in WRF. Part II: 3D
1232 simulations of actual seeding events and sensitivity tests. *Journal of*
1233 *Applied Meteorology and Climatology*, 52(6):1458-1476.DOI:
1234 <https://doi.org/10.1175/JAMC-D-12-0149.1>

1235 Xue, L., X. Chu, R. Rasmussen, D. Breed and B. Geerts, 2016: A case
1236 study of radar observations and WRF LES simulations of the impact of
1237 ground-based glaciogenic seeding on orographic clouds and
1238 precipitation. Part II: AgI dispersion and seeding signals simulated by
1239 WRF. *Journal of Applied Meteorology and Climatology*, 55(2):445-
1240 464. DOI: <https://doi.org/10.1175/JAMC-D-15-0115.1>

1241 Yoshida, Y., M. Murakami, Y. Kurumisawa, T. Kato, A. Hashimoto, T.
1242 Yamazaki and N. Haneda, 2009: Evaluation of snow augmentation by
1243 cloud seeding for drought mitigation. *Journal of the Japan Society of*
1244 *Hydrology and Water Resources*, 22(3):209-222. DOI:
1245 <https://doi.org/10.3178/jjshwr.22.209>

1246 Yuter, S.E. and R.A. Houze Jr., 1995: Three-dimensional Kinematic and
1247 microphysical evolution of Florida cumulonimbus. Part II: Frequency
1248 distributions of vertical velocity, reflectivity, and differential
1249 reflectivity. *Monthly Weather Review*, 123(7):1941-1963.DOI:
1250 [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0493(1995)123<1941:TDKAME>2.0.CO;2)
1251 [0493\(1995\)123<1941:TDKAME>2.0.CO;2](https://doi.org/10.1175/1520-0493(1995)123<1941:TDKAME>2.0.CO;2)

1252

1253 Zhang, J., Howard, K., Langston, C., Kaney, B., Qi, Y., Tang, L., ... &
1254 Arthur, A. (2016). Multi-Radar Multi-Sensor (MRMS) quantitative
1255 precipitation estimation: Initial operating capabilities. *Bulletin of the*
1256 *American Meteorological Society*, 97(4), 621-638.

1257

1258

1259

1260 **Table 1:** Compilation of current seeding methods, including comments on
 1261 some of the methods (more references can be found in WMO (2018a)).
 1262

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		
--	------------------------------------------------------------------------------------------------	--	--

1263

1264

1265

1266

1267

1268 Figure Caption list:

1269

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.

1276

1277

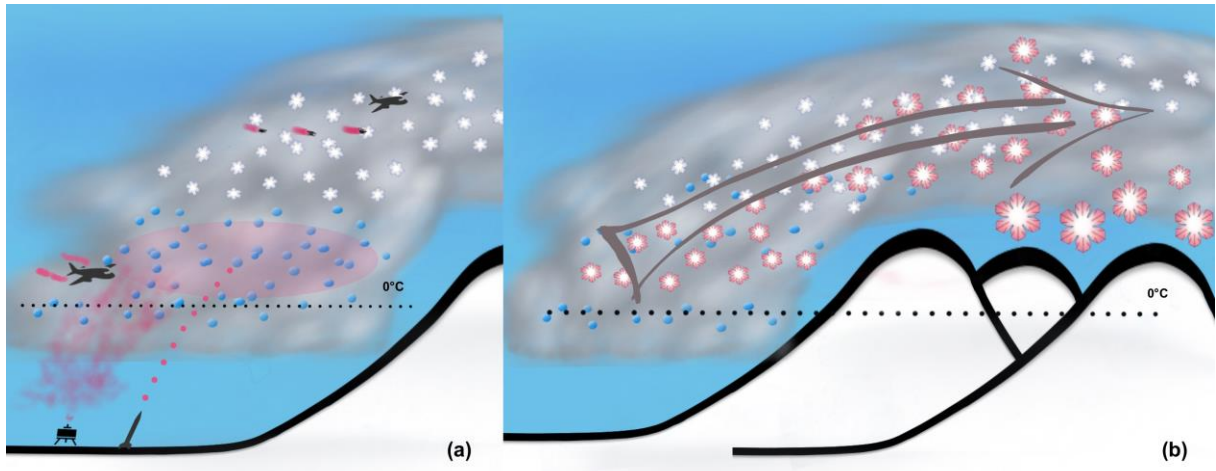
1278 Figure 2 (a) hygroscopic seeding of a convective cloud; in red: the seeded
1279 area and seeding material to be added by plane, burner or rocket; (b) the
1280 intended outcome of the seeding in red, when the added large CCN form
1281 drops that grow via condensation and trigger collision and coalescence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

1283

1284

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.

1290

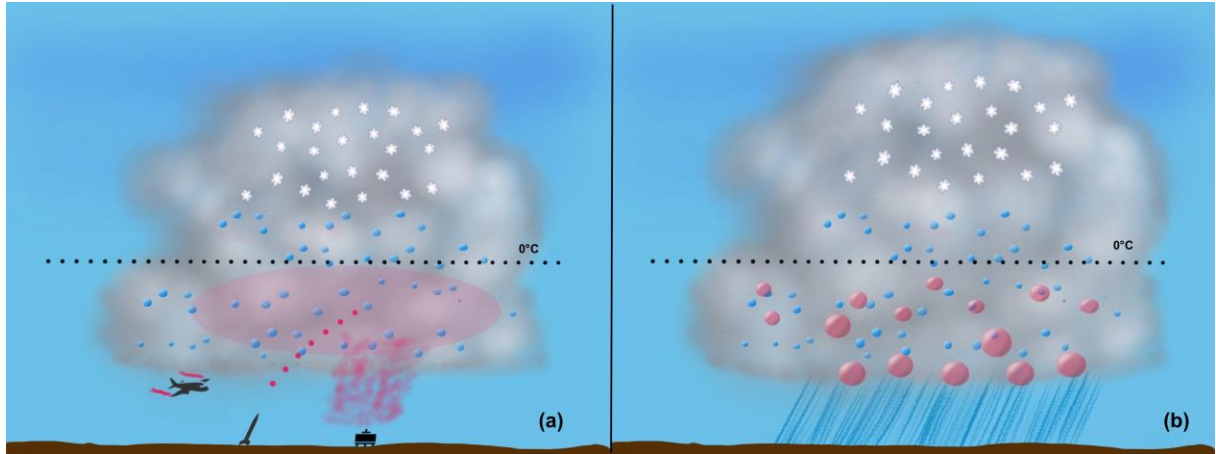


1291
1292
1293

1294 Figure 1 (a) glaciogenic seeding of an orographic winter time cloud; in
1295 red: the supercooled seeded area and the seeding material to be added by
1296 plane, burner or rocket; (b) the intended outcome of the seeding in red,
1297 when the added INP form crystals that grow via WBF effect and riming to
1298 form snow; the additional release of latent heat may invigorate the cloud;
1299 the arrow indicates the sense of the space and time evolution.

1300
1301
1302
1303

1304



1305

1306

1307 Figure 2 (a) hygroscopic seeding of a convective cloud; in red: the seeded

1308 area and seeding material to be added by plane, burner or rocket; (b) the

1309 intended outcome of the seeding in red, when the added large CCN form

1310 drops that grow via condensation and trigger collision and coalescence to

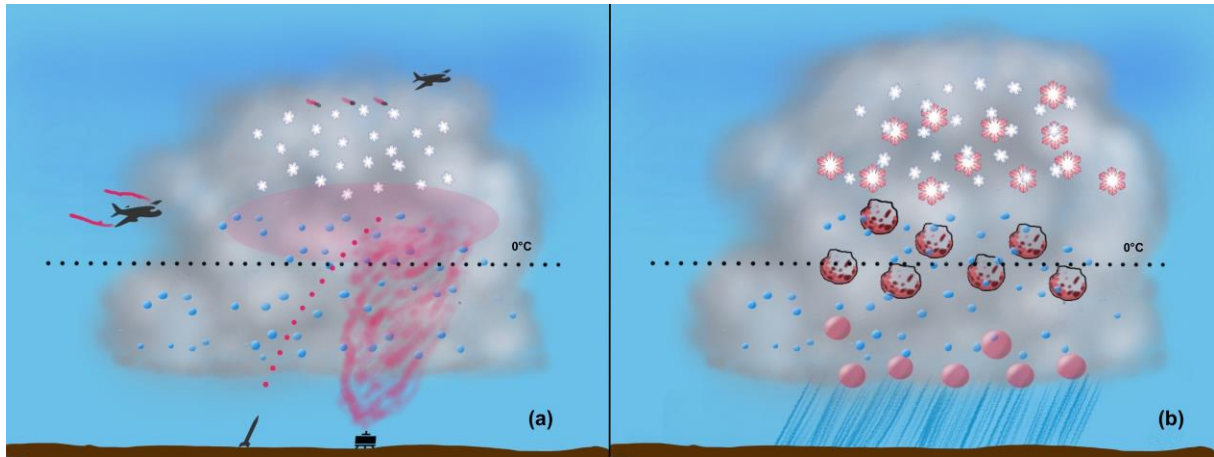
1311 form rain; the additional release of latent heat may invigorate the cloud.

1312

1313

1314

1315



1316
1317
1318

1319 Figure 3 (a) glaciogenic seeding of a convective cloud; in red: the seeded
1320 area and seeding material to be added by plane, burner or rocket; (b):
1321 the intended outcome of the seeding in red, when the added INP form
1322 crystals that grow via WBF and riming and melt below the 0°C isotherm;
1323 the additional release of latent heat may invigorate the cloud.