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

2

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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  $\mu\text{m}$  (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  $\mu\text{m}$ . 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 CO<sub>2</sub> (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 km<sup>2</sup>. 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

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799

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803

804

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1260 **Table 1:** Compilation of current seeding methods, including comments on  
 1261 some of the methods (more references can be found in WMO (2018a)).  
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<b>Seeding agent</b>	<b>Hypothesized functioning and delivery method</b>	<b>Some method details and comments</b>	<b>Some recent references</b> (for more references see WMO (2018a))
AgI, AgIO <sub>3</sub>	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 <sub>2</sub>	Glaciogenic seeding, aircraft	Cools down to -80°C and triggers homogeneous nucleation	Seto et al. 2011
Dry ice (solid CO <sub>2</sub> )	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 $\mu\text{m}$ diameter	Ghosh et al. 2016 ; Brintjes et al. 2012
Micro-powders	Hygroscopic seeding, aircraft	Optimum suggested size of NaCl crystals is 7.5-10 $\mu\text{m}$	Drofa et al. 2013
Core/shell NaCl/TiO <sub>2</sub> (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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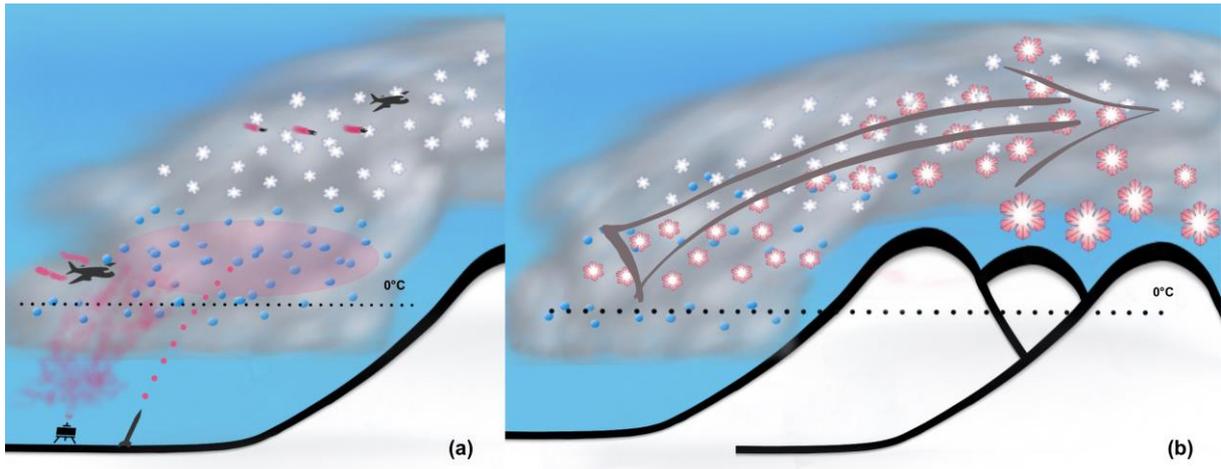
1278 Figure 2 (a) hygroscopic seeding of a convective cloud; in red: the seeded  
1279 area and seeding material to be added by plane, burner or rocket; (b) the  
1280 intended outcome of the seeding in red, when the added large CCN form  
1281 drops that grow via condensation and trigger collision and 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.

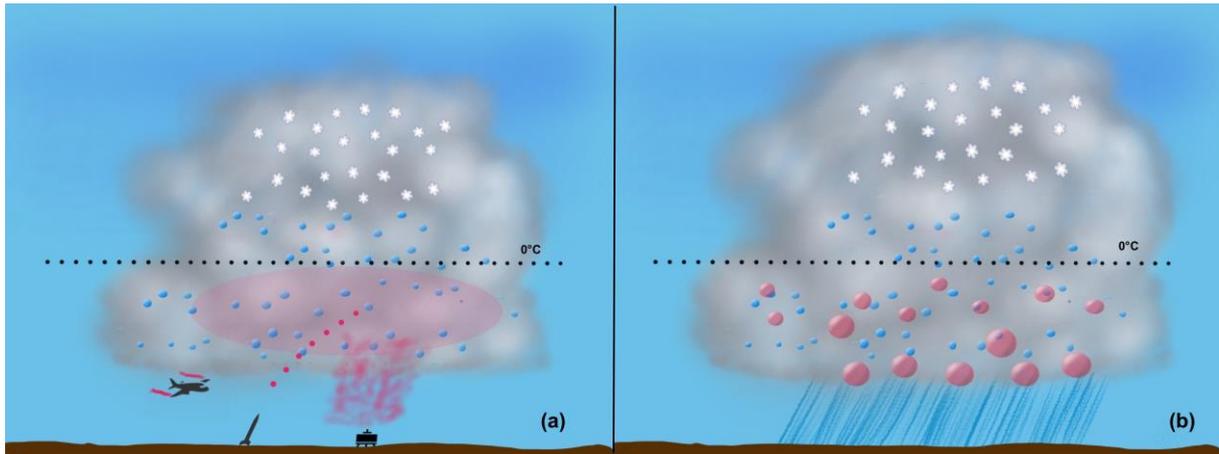
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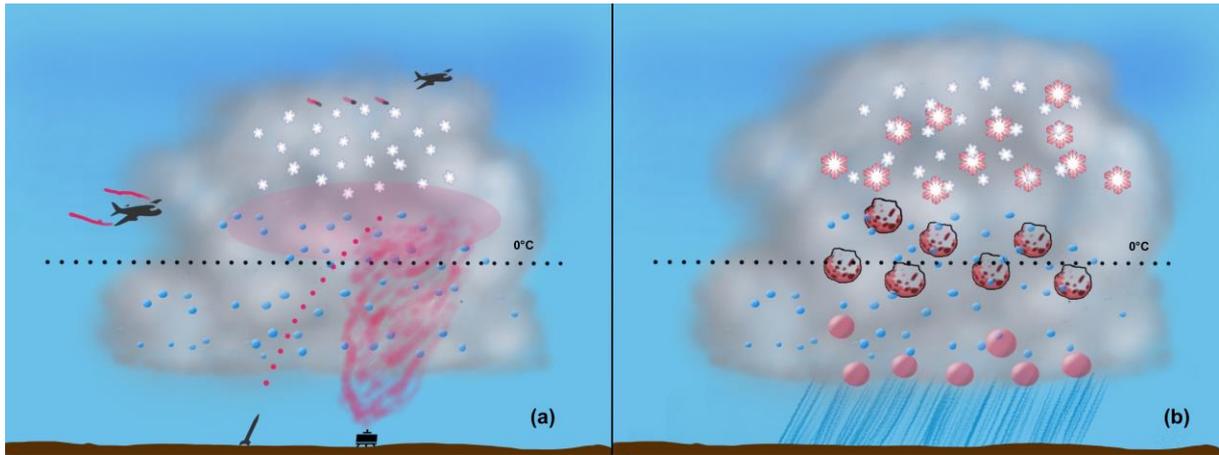
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