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## Peer Review Report on Global Precipitation Enhancement Activities

Andrea Flossmann, Michael J. Manton, Ali Abshaev, Roelof Bruintjet,  
Masataka Murakami, Thara Prabhakaran, Zhanyu Yao

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WWRP 2018 - 1

# Peer Review Report on Global Precipitation Enhancement Activities

WEATHER CLIMATE WATER



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WWRP 2018 - 1

# Peer Review Report on Global Precipitation Enhancement Activities

Authors: Andrea I. Flossmann, Michael Manton, Ali Abshaev, Roelof Brientjes,  
Masataka Murakami, Thara Prabhakaran and Zhanyu Yao

Reviewers: Zev Levin, Steven Siems and 2 anonymous reviewers



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Chairperson, Publications Board  
World Meteorological Organization (WMO)  
7 bis, avenue de la Paix  
P.O. Box 2300  
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03  
Fax: +41 (0) 22 730 80 40  
E-mail: [publications@wmo.int](mailto:publications@wmo.int)

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## EXECUTIVE SUMMARY

In a period of accelerating climate change, the continuous struggle for reliable water resources has taken renewed urgency. There are indications that an increasingly number of WMO Members are planning or actually carrying out precipitation enhancement activities in response to water shortages or other societal needs. Furthermore, the development of increasingly powerful computers as well as observation and analytical capabilities have evolved considerably, advancing our understanding of individual cloud processes and their possible interactions.

These facts have motivated the World Meteorological Organization (WMO) Expert Team on Weather Modification to review the progress made on precipitation enhancement since the last published assessments in a WMO workshop report (WMO, 2000) and a USA National Research Council report (2003).

In order to be most beneficial, this review focuses exclusively on the scientific basis for precipitation enhancement. Hail suppression, fog dispersion or harvesting as well as subjects related to geoengineering were, thus, out of scope for this current assessment. In addition, to provide the most useful information, the report focuses on the two cloud types most seeded in the past: winter orographic cloud systems and convective cloud systems. The review is structured in five thematic chapters:

### **Natural Cloud Systems and Variability**

In this section, our understanding of the natural atmosphere and its clouds are summarized. The dynamical features of the two main treated cloud systems are detailed as well as the natural microphysical processes from aerosol particles to surface precipitation.

It is now accepted that the concept of an isolated cloud is not useful, as a cloud has to be seen in a large-scale three-dimensional context, where the synoptic environment determines cloud formation and evolution on all scales. Large-scale flow and local pollution determine the ambient aerosol population that provides the cloud condensation nuclei (CCN) and the ice nucleating particles (INP) for the hydrometeors.

- Major gaps still exist in our knowledge of microphysical processes, especially associated with the formation and growth of solid hydrometeors. Secondary ice multiplication processes need further investigation. The understanding of the interactions between these processes as well as with the dynamics on all scales needs to be improved.

The huge energy associated with natural cloud systems means that it is not feasible to enhance precipitation through changes to the mass or energy balance of the system. Thus, only a precise knowledge of the system and a careful intervention via seeding with appropriate aerosol particles that augment or substitute for natural particles provide this "surgical" opportunity to enhance precipitation from some clouds.

## **Potential for Precipitation Enhancement**

Glaciogenic seeding of wintertime orographic clouds can convert inherent supercooled liquid water into snow and thus increase precipitation across water catchment-scale regions. Probably due to the relatively high constraints on the dynamics of such clouds, the reported results are rather encouraging. The stability of the flow over a mountain (represented by the Froude number) and the geometry of the mountain (represented by its aspect ratio) are determining parameters, as well as the temperature and stratification of the deeper atmosphere. Here, the overall depth of the cloud with respect to the height of cloud top and the freezing height are of crucial importance. Best results seem to be obtained for silver iodide aircraft seeding of clouds that have already a natural tendency for precipitation formation.

Due to the larger variability of the dynamical conditions and to continuing uncertainties in the underlying mechanisms, the results for convective and stratiform clouds are less conclusive. Those clouds can be seeded with glaciogenic or hygroscopic agents, which compete in different pathways with the natural particles. Here also, the location and timing of seeding inside the cloud is of utmost importance, and to intensify already forming precipitation seems to be the most promising approach.

- From our current understanding of hygroscopic seeding, it is necessary to ensure that the seeding particles are larger than the naturally-occurring aerosol particles, and this criterion may require the development of new types of seeding agents for flares.
- A glaciogenic seeding agent injected at cloud base might first act as a CCN, become involved in warm rain processes and not ascend to the altitudes where it becomes an INP. Thus, the determination of the appropriate altitude of seeding is relevant.
- The outstanding issue for convective cloud is, in addition to the uncertainties in the underlying mechanisms, the determination of the actual interactions between cloud microphysics and dynamics and their consequences for the precipitation efficiency that may provide a scientific basis for effective and efficient cloud seeding.

Other approaches to cloud modification are also considered. Ionization and electrification do not provide a sound scientific pathway for precipitation enhancement. Laser technologies might succeed in forming cloud droplets in subsaturated regions, but these droplets could not grow to precipitation due to the overall lack of humidity. There is no convincing scientific basis for the use of cannons.

## **Observations of Aerosols, Clouds and Precipitation**

The development of observation methods has contributed considerably to our advances in the understanding of the functioning of clouds and their subsequent seeding. The essential indicator of success of a precipitation enhancement project is the observation of increased precipitation on the ground above the naturally expected level. The natural variability of precipitation means that the detection of increased precipitation is a major challenge. This challenge is especially difficult for convective cloud systems, where both spatial and temporal variability are high, leading to substantial "noise" that can mask a relatively small "signal" of increased precipitation due to seeding.

Radars with a range of different frequencies and other active or passive remote sensors are deployed not only on the ground but also on aircraft platforms and satellites. Research aircraft with sophisticated instrumentation allow probing of clouds in situ, and laboratory and wind-tunnel experiments have advanced our knowledge of small scale microphysical processes.

- Given the rapid evolution of remote sensing technologies, it is important to develop robust hardware and software systems that provide accurate and consistent estimates of the derived meteorological and cloud variables.

Each seeding activity needs to be accompanied and supported by an extensive modelling activity.

### **Modelling of Natural Clouds and Seeded Clouds**

Three-dimensional mesoscale modelling of entire cloud systems embedded in a large-scale flow has become a new standard. These models are driven by the output of global or Numerical Weather Prediction models, and their nesting capabilities allow us to zoom into a region of interest. Here, their grid sizes are now approaching large eddy simulation (LES) values. Furthermore, multi-moment or bin-resolved schemes have been coupled to these dynamics, providing interesting insights into the functioning of cloud systems. Unfortunately, the sensitivity of model results to variations in the microphysics parameterization is an outstanding source of uncertainty. Also, most models do not yet take into account the ambient background aerosol population for the simulation of drop and ice particle nucleation, as well as the detailed effect of the seeding agents. The representation of the atmospheric boundary layer in a cloudy atmosphere is also a continuing challenge in weather prediction models.

- Model intercomparison projects that compare the performance of models among each other and with an observed situation are, thus, of utmost importance to understand the key parameters in microphysics and boundary layer parameterizations, to improve them and to increase our confidence in the model results.

Once exploratory seeding campaigns have been completed and deemed successful, in order to be beneficial in the context of an overall water shortage, the seeding needs to be extended to larger areas and time periods.

### **Catchment-Scale Research Projects**

The upscaling of an exploratory seeding campaign to a catchment basin-sized region requires a strict protocol. Catchment-scale experiments are invariably aimed at demonstrating an economic benefit of cloud seeding. Due to the large variability of natural precipitation, such economic cost-benefit analyses are not straightforward, even for winter orographic cloud seeding where the cloud system and target area are clearly identifiable and fixed. However, scaling-up of the effects of seeding mixed-phase convective clouds remains an outstanding challenge, partly because of the uncertainties in the physical basis of the methodology but also because of the extreme variability of convective clouds in space and time. Furthermore, cloud seeding on these scales can have environmental risks that need to be managed by careful planning and monitoring.

- Analysis of historical data should be carried out before the start of a catchment-scale experiment to estimate the probability of detection of enhanced precipitation, specifically to determine the minimum duration of the experiment. The experimental strategy needs to include randomization of seeding and a consistent methodology to support a rigorous statistical analysis of the data. The toxicity of the seeding agents for the environment need to be closely monitored, as well as other issues like a possible redistribution of surface precipitation. High resolution modelling can be of help with these issues.

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The authors of the report are:

Andrea I. Flossmann, Université Clermont Auvergne/CNRS, Clermont-Ferrand, France.

Michael J. Manton, School of Earth Atmosphere and Environment, Monash University, Australia.

Ali M. Abshaev, High Mountain Geophysical Institute of Russian Hydrometeorological Service, Nalchik, Russia.

Roelof Bruintjes, NCAR, Boulder CO, USA.

Masataka Murakami, Institute for Space-Earth Environment Research, Nagoya University, Nagoya, Japan.

Thara Prabhakaran, Indian Institute of Tropical Meteorology, Pune, India.

Zhanyu Yao, Chinese Academy of Meteorological Sciences, Beijing 100081, China.

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## 1. INTRODUCTION

The development of human societies is dependent on the availability of a reliable source of water. Thus, there has been a continuing interest in means to enhance or at least ensure rain from the clouds.

As our understanding of atmospheric processes increased, the first serious attempts at weather modification were made by seeding clouds e.g. with dry ice, silver iodide or hygroscopic particles. However, attempts then remained inconclusive, even though an increasing number of facts seemed to indicate that seeding has an effect on clouds.

In the late 1970s, the World Meteorological Organization (WMO) established the Precipitation Enhancement Project (PEP) to provide a sound scientific basis for precipitation enhancement activities by WMO Members. A key outcome of PEP was the importance of careful observations and analysis of the suitability of a potential site for precipitation enhancement (WMO, 1985). While PEP was focused on the seeding of cold winter clouds, there was growing interest during the 1990s in the potential for hygroscopic seeding of liquid clouds based on early results from South Africa (Mather, 1991). WMO co-sponsored a workshop in Mexico in 1999 to review the state of hygroscopic seeding and to identify future research needs for this approach to precipitation enhancement. A key finding of the workshop (WMO, 2000) was the need for international cooperation to develop an understanding of the physical processes associated with hygroscopic seeding.

Recognizing the need to understand the fundamental processes related to intentional and unintentional changes in the atmosphere, the USA National Research Council (2003) carried out a review of the science of weather modification. A major conclusion of the review was that future progress was dependent on an improved fundamental understanding of crucial cloud, precipitation, and larger-scale atmospheric processes. This review led to some discussion in the scientific literature by e.g. Garstang et al. (2004), List (2004) and Silverman (2003) on the scientific basis of precipitation enhancement. Levin and Cotton (2008) edited a comprehensive review of the effects of aerosol pollution on precipitation.

Levin (2009) provides a somewhat reserved review on the scientific basis of both glaciogenic and hygroscopic seeding while pointing out that orographic seeding may hold some promise. More recently, Tessendorf et al. (2015) provide a more optimistic view on the future of seeding winter orographic cloud based on progress in observational field studies and in the capabilities of numerical modelling of both mesoscale and microscale processes in the atmosphere.

This evolution of opinion reflects the fact that even though our understanding of cloud processes is still somewhat patchy, we have advanced over the last couple of decades regarding the basic physics and interaction of some of the processes, particularly due to the study of aerosol-cloud-interactions for climate purposes. The development of increasingly powerful computers has enabled the simulation of three-dimensional large-scale cloud fields holding liquid and solid hydrometeors. The development of observation capabilities has evolved considerably, in particular with respect to remote sensing as well as in situ instrumentation. Powerful radars and other active or passive remote sensors are deployed not only on the ground but also on aircraft platforms and satellites. Research aircraft with sophisticated instrumentation allow probing the clouds in situ, while laboratory and wind tunnel as well as

cloud chamber experiments have advanced our knowledge of small-scale microphysical processes.

With the help of these technological advancements, progress in our understanding of the interaction of cloud processes has been possible, providing steps towards the “further scientific advances” recommended in previous reviews. We have now a much more detailed knowledge of the overall functioning of cloud and cloud systems and the potential effects that seeding can provoke.

In the meantime, we have also begun to change the climate of our planet. Increasing concentrations of CO<sub>2</sub> and other greenhouse gases have started to raise global temperature and to move the boundaries of long established climate zones (IPCC, 2013). We are at the beginning of this process, and already water shortage in some regions is recorded beyond the normal statistical variability and the frequency of extreme events is also increasing. Numerous conflicts are erupting around water shortage and it is likely that in the future many more conflicts will be centred on water resources.

This increased pressure on water resources has initiated a renewed interest in precipitation enhancement operations. An increasing number of countries, mostly in mid-latitudes or in the sub-tropics, but also even in the tropics are planning or have launched experimental or operational precipitation enhancement initiatives.

The WMO Expert Team on Weather Modification regularly updates the WMO statement and planning guidelines on weather modification, with the most recent statement prepared in 2010 (WMO, 2010). The statement recognizes the continuing uncertainties associated with weather modification, including precipitation enhancement. The statement and guidelines aim to assist WMO Members undertaking precipitation enhancement activities. The 2017 survey of WMO Members involved in weather modification shows that precipitation enhancement activities are carried out primarily in response to water shortages affecting agriculture and other societal needs. However, some agencies recognize the value of cloud seeding to provide routine augmentation of water supplies. There are increasing activities using precipitation enhancement technologies to redistribute precipitation in order to protect urban areas or to suppress wild fires.

It is, thus, recognized that cloud seeding is occurring now in numerous countries around the world. Unfortunately, not all those seeding efforts are being undertaken with a rigorous analysis and there are even organisations that will try to take advantage of desperate situations by unfounded promises.

In order to provide guidance for future precipitation enhancement attempts, the WMO Expert Team on Weather Modification has prepared this document. It reviews the current scientific understanding of cloud physics in relation to its potential application to precipitation enhancement projects. With its purely scientific aim the review will not address detailed operational cloud seeding issues.

The review starts with a chapter describing natural clouds and their variability. We understand now that we need to study a cloud within its overall natural environment. In the past, a cloud was often considered as a stand-alone feature and was studied, modelled and seeded as such. Now we know that even though seemingly isolated, a cloud is generally part of an environment, extending over tens if not hundreds of kilometres. The flow field in the cloud region links the individual cells, thus influencing each other. Due to the interaction between clouds and their environment, air parcels move in and out of a cloud. Air will leave the cloud through the upper or a lateral boundary, evaporate and enter the same or another cell at a later time. It also carries the aerosol particles present in the atmosphere that are necessary to form the hydrometeors. As a consequence, seeding at one time and place can sometimes seem to influence clouds much later or at a different place.

Ambient aerosol particles show a quite large natural variability, depending on the history of the air mass. We need to distinguish air masses of maritime origin, carrying few and large soluble particles, from polluted air masses where the aerosol particles are numerous, small and often formed by condensation of combustion products. We know that, when serving as cloud condensation nuclei and ice nucleating particles, the ambient aerosol particles influence the number and size distribution of the hydrometeors.

In particular, when clouds are seeded, particles are added artificially at specific locations in the cloud. However, the added particles obey the same physical principles as the background particles, but the differences in concentration and their activation are meant to override the natural cloud evolution. It is evident that this competition between the seeding particles and the naturally present particles needs to be better understood in order to increase the success of precipitation enhancement initiatives.

Even though seeding by particles is currently the most promising approach, one section in the seeding chapter considers other techniques that are sometimes proposed to enhance precipitation.

Most cloud seeding experiments in the past and present primarily focus on two cloud types:

1. Mid-latitude extratropical cyclones or frontal systems. These systems can result in winter orographic cloud systems and can contain embedded convection or post-frontal cumulus clouds.
2. Convective cloud systems: These systems often occur during the summertime over mid-latitude regions but can occur throughout the year in tropical and subtropical regions. These systems are usually associated with surface heating and can also be triggered by orography or convergence zones. These convective systems can be comprised of a liquid ( $>0^{\circ}\text{C}$ ), mixed phase (0 to  $-40^{\circ}\text{C}$ ) and ice phase ( $<-40^{\circ}\text{C}$ ). In rare instances, the convection will only contain a liquid phase while in deeper convective systems all phases will be present.

Although there may be some interest in other cloud systems such as stratus or stratocumulus low-level clouds and altostratus and nimbostratus mid-level clouds, these have not been the primary targets of cloud seeding experiments to enhance precipitation in the past. The focus of past cloud seeding experiments on wintertime orographic clouds and convective clouds will guide the current review.

Chapters on recent developments in cloud observation and modelling follow, as they provide the means to plan, execute and evaluate a seeding experiment.

A final chapter will give advice for the design and set-up of a catchment basin-sized precipitation enhancement campaign, as well as guidance for the evaluation of the outcome, incorporating the science and the tools and means discussed in the previous chapters. This review of the state of the art of our current knowledge of precipitation enhancement concludes by indicating the most important gaps in our knowledge. Some recommendations regarding the most urgent research topics are hoped to stimulate further research and potential funding.

In order to be most beneficial, this review will only focus on the scientific basis for precipitation enhancement topics. Hail suppression, fog dispersion or harvesting as well as subjects related to geoengineering are, thus, out of scope for this current assessment.

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## **2. NATURAL CLOUD SYSTEMS AND THEIR VARIABILITY**

### **2.1 General introduction**

Clouds and rain are among the most important and least understood components of the climate system (Boucher et al., 2013), and cloud processes are also one of the largest sources of uncertainty in numerical models for weather and climate (IPCC, 2013). About two-thirds of the Earth's albedo is controlled by clouds (Trenberth et al., 2009), which play an important role in the earth's radiation and water budgets. To scale this effect, the anthropogenic greenhouse gases warming effect is on the order of few percent of the overall cloud effect on the planetary radiative budget (Boucher et al., 2013). In this framework, rain can be viewed as the end result of a chain of complex processes both microphysical and dynamical, which need to be understood in order to predict fresh water availability.

Consequently, cloud physics is a highly interdisciplinary field of research: when trying to predict cloud and rain behaviour one must consider interactions and feedbacks between the synoptic, dynamic, thermodynamic, microphysics, electrical and radiative processes at all scales.

The fact that clouds are visible by the naked eye indicates that clouds contain particles that are large enough to scatter light in the visible wavelengths. These hydrometeors, can be either water droplets or in colder environments mixed-phase and ice particles. In order to form these hydrometeors, the relative humidity has to exceed the saturation level and liquid or solid particles suspended in the atmosphere need to serve as cloud condensation nuclei (CCN) or ice nucleating particles (INP). Further growth and development of clouds into precipitation depends on several complex nonlinear interactions.

As pointed out in the introduction, the review will focus on the two currently most popular types of precipitation enhancement targets. One concerns wintertime orographic clouds that have been studied for many years. Their seeding with glaciogenic particles has the potential to trigger snowfall, in order to increase the precipitation in mountainous water reservoir regions. The second type concerns mixed phase convective clouds that are seeded with hygroscopic or glaciogenic particles in order to trigger liquid or mixed phase precipitation.

This focus will guide the discussion of the natural cloud systems below.

### **2.2 Formation of clouds and the role of aerosol particles**

Small particles suspended in the atmosphere are called "aerosol particles". They are found everywhere even in very remote and clean areas. Their sizes can range from few nanometres up to tens of micrometres. Table 2.1 gives typical number and mass concentrations near the surface.

**Table 2.1. Typical number and mass concentrations of atmospheric aerosol particles close to sea level and the corresponding mean radius (adapted from Warneck, 2000).**

Location	Number concentration ( $cm^{-3}$ )	Mass concentration ( $\mu g/m^3$ )	Mean radius ( $\mu m$ )
Urban	$10^5$ - $10^6$	100	0.03
Rural continental	$\sim 10^4$	30-50	0.07
Maritime	100-600	10	0.16

Whitby (1978) suggests a characterization of the aerosol particle spectrum following their size and their predominant behaviour. Particles with radii  $<0.1 \mu m$  are called *Aitken particles* or *transient mode particles*, because of their short life times. Particles between  $0.1$  and  $1.0 \mu m$  radius are called *accumulation mode or large particles*, while those larger than  $1.0 \mu m$  radius are called *giant or coarse mode particles*. Recently, as the possibility for their observation became available (Tomasi et al., 2017), this scheme has been enlarged for the *nucleation mode particles* smaller than  $0.01 \mu m$ .

Depending on their formation pathway, aerosol particles have quite different chemical composition: the mechanically created coarse mode particles consist mainly of soluble sodium chloride and ammonium sulphate from sea salt in marine locations; or insoluble minerals (e.g. silicate), wind blown dust, volcano, diesel exhaust particles, bacteria or plant debris in continental areas. Due to their size, they fall out within hours due to gravitational settling. The smallest nucleation mode particles can be soluble or insoluble, relatively rich in metals and elemental carbon from combustion. They form through hot vapour condensation, or low temperature binary or ternary condensation from the vapour phase including organic carbon from vegetation. The particles being so numerous further grow by condensation of gases and undergo frequent collisions, and they aggregate readily to form larger particles. They therefore also have a short lifetime on the order of hours. Only the large or accumulation size particles experience longer lifetimes in the atmosphere that can amount to days or even weeks. Their main removal process is linked to clouds, as they are generally good cloud condensation nuclei and form cloud droplets (see below). This process is often called "rain out". If the cloud develops rain, then the aerosol particles inside drops are removed from the atmosphere with the raindrops. Other ambient particles can be captured below the cloud by falling raindrops ("wash out").

Due to their size and the dominant formation at the earth's surface, aerosol particle number concentrations decrease rapidly with height.

For further information on the formation and composition of atmospheric aerosol particles see e.g. Warneck (2000).

Aerosol particles are mandatory for the formation of clouds as they provide the surface on which liquid or solid condensation is initialized. Most seeding initiatives add particular aerosol particles to the cloud that compete with the naturally present particles.

### **2.2.1 Formation of drops on cloud condensation nuclei (CCN)**

Due to their different formation pathways, aerosol particles have a variable chemical composition and size (Semenuik et al., 2014). As most particles contain some soluble material, they will take up some water vapour depending on the ambient relative humidity and swell. The particles provide the surface on which condensation will occur and the eventual salt content of the particles will further help to decrease the saturation vapour pressure. The combined expressions of the curvature (Kelvin) and the solution (Raoult) effect yield the so-called Köhler equation which describes the equilibrium size of an aerosol particle of a given size and chemical composition (for details see Pruppacher and Klett, 1997). The maximum of the curve described by the Köhler equation is called the "critical radius". Humidified aerosol particles having radii greater than the critical radius don't need a further increase in humidity to grow. They are, then, called "activated" or cloud condensation nuclei (CCN).

From Köhler theory it can be derived that the larger and more soluble an aerosol particle, the more easily it serves as a CCN (additional information regarding ion effects on heterogeneous nucleation appears in Section 2.3.2 below). For the typical supersaturations encountered in clouds, depending on the solubility of the particles, aerosol particles as small as 0.02  $\mu\text{m}$  dry radius (around 0.1  $\mu\text{m}$  wet radius) can serve as CCN. Thus, the updraft velocity, which causes the supersaturation, together with the ambient aerosol particle spectrum, determines the number and size of the nucleated cloud droplets. Larger aerosol particles acting as cloud condensation nuclei need only a small supersaturation ( $\approx 0.001\%$ ) due to their small curvature, to form cloud droplets. But smaller CCN needs much higher supersaturations.

The number of nucleated drops is, thus, a complex function of the number of aerosol particles that serve as CCN which in turn depend on their size distribution, their chemical composition, the updraft velocity and the resulting supersaturation. The parameterized relationship  $N=cS^k$  provides an approximate value for the number of nucleated drops as a function of the supersaturation where the constants  $c$  and  $k$  are tabulated for different air masses (Twomey, 1959). More accurate methods can also be used to relate the number of CCN directly to the Köhler formula of the aerosol particles (Flossmann and Wobrock, 2010).

Furthermore, when the first and largest aerosol particles are activated, they immediately start to grow by condensation, reducing the supersaturation for the remaining CCN. In fog dispersion this mechanism allows to evaporate the small droplets, whose vapour then condensate on the seeded particles, allowing to dispersed the liquid and vapour water onto fewer droplets that grow faster and precipitate (Reuge, 2017). Different CCN result in quite different drop spectra forming in a clean air mass (wide spectra) with respect to those in a polluted air mass (narrow spectra), even for identical supersaturation conditions. Generally, it is found that low CCN concentration implies low concentration of relatively large droplets, whereas high CCN concentration implies more numerous but smaller initial droplets (Squires, 1958; Squires and Twomey, 1960).

### **2.2.2 Formation of ice crystals on ice nucleating particles (INP)**

Even though supercooled water in the atmosphere can exist down to  $-35^\circ\text{C}$ , cloud ice starts to form once the temperature drops below about  $-5^\circ\text{C}$ . Even today, large uncertainties persist

regarding the exact pathways of ice formation and on the importance of secondary ice formation processes.

We know that ice crystals can form homogeneously, that is only implicating H<sub>2</sub>O and eventually dissolved substances, at temperatures below -35°C. At all higher temperatures, an ice nucleating particle (INP) is needed to trigger the formation of ice (Vali et al., 2015; Pruppacher and Klett, 1997; Herbert et al., 2015). INPs form a small subset of the overall aerosol particle population. Heterogeneous ice nucleation refers to a process where the presence of a foreign substance is necessary for ice formation. This foreign substance is provided by the undissolved part of atmospheric aerosol particles present inside the liquid phase or outside, serving as an organizing surface for the developing ice lattice. There is evidence that INP larger than 0.1 µm diameter are more effective in initiating ice due to the larger probability for ice active sites to exist on their surface. Furthermore, the roles of the insolubility of INP, the chemical bond requirements (water must be able to make chemical bonds with the INP surface) and the crystallographic structure of the INP that templates ice are highlighted by observations. These requirements favour INP from mineral dusts and biological species (pollen, bacteria, fungal spores and plankton), as well as carbonaceous combustion products and particles of volcanic origin. Temperature, ice nucleus diameter, and contact angle seem to be among the dominant factors that increase INP potential (e.g. Pruppacher and Klett, 1997; Kanji et al., 2017).

In the presence of INP, ice can form from vapour or from liquid, providing two basic pathways called deposition nucleation and freezing nucleation. For freezing nucleation, different modes can be distinguished, depending on the exact pathway of interaction between the liquid and the solid phase during ice formation. The distinctions of deposition and freezing nucleation below refer to Vali et al. (2015, 2017) while in the past slightly different definitions were also used (Hoose and Möhler, 2012).

Deposition nucleation generally refers to the process where atmospheric water vapour directly deposits on INP particles. These particles may contain some liquid attached to them, as most atmospheric particles are wettable, however, they are not activated into cloud droplets. Thus, in order for deposition nucleation to occur, the atmospheric water vapour needs to be supersaturated with respect to ice, but could be subsaturated with respect to liquid water, conditions mostly linked to lower temperatures. The role of the INP type and ice supersaturation has been found from observations, but there may be a reduction of deposition nucleation potential if the INP, e.g. mineral dust, is coated, thus covering the active sites.

Freezing nucleation occurs within a body of supercooled liquid water due to the presence of an INP. Mainly, three different modes are distinguished here: contact freezing, condensation freezing and immersion freezing.

For contact nucleation, airborne INP collide with pre-existing supercooled drops and freeze them. However, as natural INP are often larger than 0.1µm, inside cloud they probably have been activated already during drop nucleation; and so, this process will probably mainly be found at the boundaries of clouds or below cloud in supercooled precipitation. For this process to be active, the air should generally be subsaturated with respect to water and probably also with respect to ice (in ice supersaturated regions, deposition nucleation would occur preferably.) Only very few measurements of the contact nucleation process exist, and they do

not allow a definite conclusion regarding INP size and temperature dependency. However, the strict conditions for its occurrence suggest a lower importance of this process.

Condensation freezing (also often called "condensation followed by freezing") refers to the process where liquid drops freeze, due to the fact that their CCN are also acting as INP. This can be expected to be an important process, as INP are generally large and even when completely insoluble but wettable (hydrophilic), they should nucleate droplets easily via the Kelvin (size) effect alone. This process will form rather small ice crystals in the region where the air is supersaturated with respect to water and consequently more supersaturated with respect to ice, assuring further rapid solid condensation growth of the ice crystals.

Finally, immersion freezing refers to the process where drops freeze due to the presence of an INP. While the term immersion freezing is used by Vali et al. (2015, 2017) as a synonym for freezing nucleation in general, it is also often used for the remaining processes that are neither contact nor condensation freezing, but where a drop freezes while being transported into colder regions. This decrease in temperature would activate some previously uptaken INP and initiate the freezing process. The uptaken INP can result from nucleation scavenging of a CCN or from a later impaction scavenging of ambient aerosol particles.

As cloud drops collide and coalesce among each other and with ambient aerosol particles, in the course of time and with increasing size the chance for the drop to contain an INP increases.

In addition to the type of active freezing mode, all observations highlight the importance of the chemical composition of the INP. While mineral dust particles as well as carbonaceous combustion products and volcanic ash are active INP below  $-10^{\circ}\text{C}$ , only biological species (pollen, bacteria, fungal spores and plankton) are known to act at temperatures above  $-10^{\circ}\text{C}$  even though the exact mechanism by which bacteria act as INP is not yet fully understood.

The distinctions between the different heterogeneous ice nucleation modes are generally accepted (Vali et al., 2015) and it is understood that the number of INP increases rapidly with decreasing temperature and increasing supersaturation. However, it is currently not possible to predict the INP concentration or even the specific ice formation mechanism based on aerosol number and chemistry information. This deficiency results from the fact that laboratory and in situ measurements of ice nucleation are quite difficult (for a detailed review of the heterogeneous ice nucleation observations see e.g. Hoose and Möhler, 2012; Kanji et al., 2017). These observational challenges also mean that there is no routine monitoring of INP concentration or composition, and so the natural variability in space and time of INP is uncertain.

Furthermore, observed ice number concentrations may be biased due to ice multiplication processes (Field et al., 2017) occurring naturally in some clouds and specific temperature regimes or as an artefact during sampling. One well-identified ice multiplication process is the Hallett–Mossop processes (Hallett and Mossop, 1974) that is found to be an important mechanism in intense deep convection (Phillips et al., 2007). Recently, also other ice multiplication mechanisms have been observed (Leisner et al., 2013; Lawson et al., 2017).

## 2.3 Cloud microphysics

Freshly nucleated cloud droplets or ice crystals need to grow from a size of a few micrometres to hydrometeors with fall speeds exceeding the general updraft velocity in a cloud in order to arrive at the ground as solid or liquid precipitation.

### 2.3.1 Growth of cloud particles

The initial processes taking place in clouds (with cloud-bases below the freezing level) are the nucleation and growth of water drops (the so-called "warm" processes). After activation (see Section 2.2.1) droplets can grow by condensation, but these diffusion processes are relatively slow. With the generally low supersaturation levels found in clouds (below 1%) and for common droplet concentrations (order of magnitude of around  $100 \text{ cm}^{-3}$ ), it will take much longer than the cloud's lifetime for a cloud droplet (with a typical size of  $10 \text{ }\mu\text{m}$ ) to grow by condensation alone to the typical size of a raindrop ( $\sim 1000 \text{ }\mu\text{m}$ ) that can overcome the cloud's updraft and reach the surface.

A more efficient growth mechanism that will support a faster transition of cloud droplets to raindrops (in models often called "autoconversion"), involves collisions and coalescence in which the larger droplets collect the small ones and grow to form raindrops in timescale of tens of minutes (depending on cloud type). The hydrometeor fall speed (terminal velocity,  $V_t$ ) is the velocity the particle will reach, once a balance between gravitational and drag forces is achieved.  $V_t$  is a monotonically increasing function of particle size. It increases rapidly (squared with the particle radius) for small hydrometeors, and as the particle grows  $V_t$  increases more slowly until saturation; for example  $V_t$  saturates at values less than 10 m/s for drops with radii  $\sim 4 \text{ mm}$  (Pruppacher and Beard, 1970). We note that ground precipitation is measured in terms of rain rate i.e. a flux: volume of rain per unit area per unit time and it is usually expressed in  $\text{mm hr}^{-1}$ . It inherently relates to the volume of the drops and their fall velocity.

The efficiency of the transition from cloud droplets to raindrops is critically important in determining the cloud properties and rain formation. This efficiency strongly depends on the relative difference between hydrometeor  $V_t$ , and therefore on the droplet size distribution (Gunn and Phillips, 1957; Squires, 1958; Warner, 1968; Twomey, 1977). Large droplets and large variance in their sizes tend to increase the transition efficiency. As cloud spectra depend on the aerosol particles on which they form, clouds that develop in a very pristine environment (with around  $10 \text{ CCN cm}^{-3}$ ) have limited overall droplet surface area, and therefore they condense less water. In this case the small number of large droplets in a wide drop spectrum with largely different  $V_t$  may collide and form raindrops in earlier stages. On the other extreme, a very polluted environment (order of 1000s of  $\text{CCN cm}^{-3}$ ) implies activation of many droplets that compete for the available water vapour. The likelihood of collision and coalescence in a narrow drop spectrum when all droplets are small (order of few microns) and have similar small  $V_t$  is reduced dramatically and implies therefore a reduction in the efficiency of the transition to rain. For shallow clouds this might even mean no rain development (Rosenfeld, 1999) if the cloud top height is lower than the height where significant coalescence starts. In this case, the addition of giant CCN can accelerate precipitation formation through a broadening of the drop spectrum (Yin et al., 2000b).

On the other hand for deeper clouds, a reduction in the collection efficiency implies delay in the onset of liquid rain but not necessarily reduction in the overall amount (Wang, 2005; Seifert and Beheng, 2006; Fan et al., 2007; Lee and Feingold, 2010; Gayatri et al., 2017; Koren et al., 2014). A nearly linear relationship was obtained for the droplet number concentration and depth of rain initiation, indicating that more CCN are required for suppressing precipitation in deeper clouds. Aerosol particles could increase this depth beyond the actual cloud depth as indicated from observations (Konwar et al., 2012; Goren and Rosenfeld, 2015). Collisional or spontaneous breakup (Pruppacher and Klett, 1997) will limit the upper size of the raindrops.

For clouds that reach higher in the atmosphere or that develop above the freezing level, temperature decreases sufficiently to consider additional processes for the formation and growth of mixed-phase and ice hydrometeors. Depending on temperature, supersaturation and the availability of INP (Section 2.2.2), ice crystals can form. After the homogeneous or heterogeneous formation of these ice particles they grow by solid condensation, since at this stage the cloud is saturated or supersaturated with respect to ice. This represents a favourable environment for rapid depositional growth of ice as long as there is liquid water that can evaporate and maintain the supersaturation conditions for ice (the so-called Wegener-Bergeron-Findeisen process (WBF); Wegener, 1911; Bergeron, 1935; Findeisen, 1938). The ambient conditions determine not only the growth rate but also the crystals' habit, which is invariably a hexagonal structure but with different axis ratios and densities.

In situations where large drops are present, secondary ice formation can occur (Field et al., 2017; Patade et al., 2015; Lawson et al., 2017). This subsequent initiation of a natural seeding (ice splintering) process together with the WBF process can rapidly deplete the cloud liquid water content. The WBF mechanism can only occur under a limited range of conditions. The WBF mechanism requires that the vapour pressure exceeds ice saturation and is still below liquid saturation. Fan et al. (2011) have shown that vapour pressure often exceeds saturation for both liquid and ice and both droplets and ice particles grow simultaneously. Although the INP concentration is significantly lower than that of CCN, it is critical as it enhances the WBF process and riming (Fan et al., 2011). An increase in aerosol particles that can act as INP may be expected to nucleate more ice crystals, which could facilitate diffusional growth or riming due to increased conversion from liquid to ice. This process is targeted e.g. in wintertime orographic clouds with regions of supercooled liquid water (SLW) where the drops are generally too small to form precipitation. This way, through the cloud glaciation effect, a cloud can glaciate more rapidly and can generate more precipitation. Storelvmo (2017) reviews progress made in aerosol effects on mixed phase clouds and emphasises the need for more in situ observations in mixed phase clouds.

Summarizing, the growth by diffusion is generally not efficient enough to create precipitation within the limited timeframe of a cloud lifetime, and so the collection processes need to enhance the growth rate. Ice crystals can capture and freeze (completely or partially) supercooled drops and create rimed frozen particles or mixed phase particles (graupel or hail). Furthermore, ice particles can stick together and create aggregates.

Riming growth is reported to be prevalent in most convective clouds, and the BWF process favours aggregation producing snowfall, attributing those processes a particular importance for seeding efforts. The dependence of those mixed phase and ice growth processes, however, on

the number of INP is still not known. Regarding the efficiency of the riming process, some modelling studies show enhanced riming in a polluted environment due to efficient collection of more numerous supercooled smaller drops by ice particles (Wang, 2005; Fan et al., 2007; van den Heever et al., 2006). On the other hand, some studies showed less graupel production due to an insufficient number of large drops that can freeze and create graupel embryos (Seifert and Beheng, 2006; Teller and Levin, 2006; Storer and van den Heever, 2013).

The microphysical and dynamical processes are tightly coupled, and the overall rain efficiency depends on the type of cloud or cloud system, the environmental stability, the CCN and IN populations, the type of rain processes involved (liquid, mixed or ice) and the wind field.

### **2.3.2 Electrical processes in cloud**

The growth processes discussed above are based on dynamics and thermodynamic properties. As hydrometeors are exposed to the atmospheric electrical field, electrical processes involving atmospheric ions may also influence the formation and evolution of cloud droplets and ice particles.

Natural terrestrial radioactivity, cosmic ray ionization and lightning activity lead to the formation of ions (electrically charged atoms or molecules) and charged aerosol particles even in fair weather (away from thunderstorms). The natural environment contains both positive (hydrogenic) and negative (oxygenic) ions. Charging occurs naturally due to cluster ions – also known as small ions – formed from background radioactivity and cosmic rays.

The natural electrified state of the atmosphere has been studied for over a century (Wilson, 1920; MacGorman and Rust, 1998); however, the effect of ionization on the physical properties of aerosols and clouds has rarely been studied in its own right except in thunderstorms. In 1949, Vonnegut began experimenting with the effects of weak electric forces on water droplets, suggesting a possible increase of drop coagulation (Moore and Vonnegut, 1960).

Atmospheric aerosol particles carry a slight net charge due to the capture of cluster ions, as their polar properties slightly differ between positive and negative ions due to their different chemistry (Harrison and Carslaw, 2003). Ions with different polarity attract each other, attempting to create an electrically neutral compound. Theoretical considerations indicate that, in some limited situations with appreciable particle charging, charge can modify the action of aerosol particles as CCN, stabilizing the droplets formed (Harrison and Ambaum, 2008). A more widespread consequence of charge is, however, through an electrical effect on droplet-droplet collisions, which are more likely to yield successful coalescence when the droplets are charged (Klimin et al., 1994). In addition, especially with larger drops, the collision has to be complemented with coalescence. The approaching drops become distorted, with two flat surfaces approaching each other. Some bridge must form for them to merge, and this process can be enhanced by electrical effects. At small distances, it has been recognized (Lekner, 2012) that even droplets with like charges will experience attractive forces, because of the polarization of one droplet from the charge carried by the other. The overall effect of charging is to increase the collision efficiency, particularly for small droplets between which the basic collision efficiency is otherwise negligible.

Studying the influence of electric charges and fields on silver iodide particles (0.01 - 1  $\mu\text{m}$ ) formed through thermal sublimation and having initial positive charge of  $10^{-18}$ - $10^{-15}$  C, Adzhiev and Kalov (2015) concluded that their ice-forming activity depends on the magnitude and sign of the electric potential of the environment. A negative potential leads to an increase of temperature of ice-formation and ice-forming efficiency of 10-50% at a given temperature. Inversely, a positive potential promotes deterioration of ice-forming characteristics of AgI. Thus, silver iodide is more effective as an ice-forming agent in negatively charged clouds parts. Williams (2009) reviews the means through which weather and climate variations affect the global electrical circuit, and he comments on the potential for the global electrical circuit to affect weather and climate. He concludes that there is little evidence for the effectiveness of the proposed microphysical processes influencing the precipitation efficiency of cloud.

## **2.4 Cloud systems of interest in weather modification**

### **2.4.1 Introduction**

The cloud systems of most interest in weather modification are wintertime orographic and convective cloud systems (see Chapter 1). There has been little effort on the seeding of other systems such as stratiform clouds. In both cloud systems this report focuses on, there can be individual cells embedded within a larger mesoscale framework. Thus the relevant time scales for these clouds vary from a few minutes for isolated convective clouds to days for the synoptic scale systems such as wintertime fronts.

Evaluation of the efficacy of any precipitation enhancement technology depends ultimately on a demonstration of an increase in precipitation at the ground above the expected level of natural precipitation. For wintertime orographic clouds, the distribution of natural precipitation is largely determined by the orography interacting with synoptic-scale systems. Thus, provided that any embedded convection is not too great, the spatial and temporal distribution of precipitation on the ground can be estimated with some accuracy. On the other hand, convective clouds lead to precipitation that is highly variable in space and time. This variability of the natural precipitation provides a challenge in identifying any increase in local precipitation due to cloud seeding.

### **2.4.2 Wintertime orographic cloud systems**

Mid-latitude cyclones are the most significant producers of precipitation in mid-latitudes. They form in association with synoptic scale waves in the westerlies (Houze, 1993). Most of them are frontal cyclones that are characterized by systematic cloud patterns along the fronts (zones of sharp temperature and humidity gradients, baroclinic zones). Their typical size is hundreds of km and they last for days (up to a week). In a simplistic description, a frontal low is composed of three main sectors of active precipitation: The warm front that creates stratiform clouds (nimbostratus), the cold front with convective clouds (cumulus and cumulonimbus) and the cold sector (post frontal) with convective but less developed clouds (the Norwegian model, Bjerknes and Solberg, 1922).

Wintertime frontal systems passing over mountainous areas tend to have enhanced precipitation on the windward side and reduced precipitation on the leeward side. Convection tends to be invariably associated with these clouds even within a prevailing stratiform cloud

system. The low level flow of wintertime fronts tends to be unstable, so that the cloud rises over (rather than moves around) the orography. The rising moist air on the windward side generates condensation or freezing. Provided that the freezing level is below the peak of the ranges, supercooled liquid water rather than ice particles tend to be generated. The microphysical changes lead to an enhanced release of latent heat, which will induce further convective mixing. As the air passes over the summit and on to the lee-side, the microphysics will continue to evolve, depending on the detailed dynamics. The interaction between the microphysics and dynamics affects the distribution and even quantity of precipitation on the ground, but these interactions are not yet fully understood.

The spatial and temporal distribution of precipitation produced over (and near) mountains is determined by a combination of the microphysical processes of particle growth, the dynamics of the airflow, and the thermodynamics of moist air (Houze, 2012). In particular, Watson and Lane (2012; 2014) and Geerts et al. (2015) explore the sensitivity of orographic precipitation to the geometry of the terrain and to the low-level stability of the flow. For wintertime frontal systems, the precipitation distribution across the ranges tends to be sensitive to the wind speed (Manton et al., 2017).

### **2.4.3 Convective cloud systems**

The convective cloud systems suitable for seeding tend to be generated by surface heating. These cloud systems can vary from small fair weather cumulus (with spatial scale of a few km and lifetime of tens of minutes) to deep cumulus or deep thunderstorms and mesoscale convective complexes (100 km wide and timescale of several hours). The cloud systems suitable for seeding tend to have a warm cloud layer of significant depth (depth between cloud base and freezing level), so that condensation, collision and coalescence are important in the initial microphysical development of the cloud. Moisture in thermals rising from the surface condenses at cloud base leading to the release of latent heat and enhanced convection.

When the CCN concentration is low, the available water is shared by a small number of droplets that grow rapidly by condensation and collision-coalescence. Provided the warm layer depth is greater than 1-2 km, these warm cloud processes lead to the formation of raindrops and hence precipitation at the surface, provided the subcloud layer is not too dry. On the other hand, when the CCN concentration is relatively high due to natural and/or anthropogenic activities, the droplet sizes tend to be much smaller and collision-coalescence is delayed. In these circumstances, the growth of raindrops can even be completely suppressed. Hygroscopic seeding is targeted to remedy this problem. Otherwise, the absence of rain formation can lead to very high cloud liquid water content at greater altitudes. Recent studies (Fan et al., 2018) also emphasise the importance of aerosol particles of smaller sizes (< 50 nm) typically from anthropogenic origin that may invigorate deep clouds and illustrate the importance of the knowledge of complete aerosol particle size distribution.

When cloud top extends beyond the freezing level, there is potential for cloud drops to be converted to ice (compare Section 2.2.2). The vapour pressure over ice is lower than that over water. The ice particles can grow rapidly, leading to precipitation through the WBF process. This pathway is targeted in glaciogenic seeding. The latent heat of sublimation being larger than the latent heat of condensation, there is enhanced convection associated with the transition from liquid to ice or mixed phase cloud processes. Once ice particles are formed the

collision-coalescence process is enhanced due to the larger sizes and greater fall velocities of ice particles.

For both high and low CCN cases, there are complex feedbacks between the microphysics and dynamics. The dynamics involves both convection-scale processes within a cloud cell and the mesoscale flows influencing the interactions (such as merging) between individual clouds. Cumulus cloud merging is a complex dynamical and microphysical process in which two convective cells merge into a single cell. Observations and numerical simulations have shown a substantial increase in the maximum area, maximum echo top, maximum reflectivity, precipitation intensity and precipitation flux as a result of merging processes (Sinkevich and Krauss, 2014; Krauss et al., 2012; Popov and Sinkevich 2017). It was shown that the merged storm became larger and more severe than the sum of the two parts prior to merging. However, the details of these processes are not well documented or understood.

The diurnal cycle of convective clouds and precipitation are largely determined by surface heating. Solar heating and the associated surface fluxes induce boundary layer convection that commonly triggers shallow clouds in the morning. Congestus or cumulonimbus clouds are formed in the afternoon, which can develop into mesoscale convective clusters, which then may continue to precipitate into the following morning. Major factors affecting the evolution of convective clouds include moist convection in the boundary layer below cloud base, as well as local forcing due to orography or mesoscale circulations. Such processes determine the strength of convective core updrafts and the fractional cloud cover, and they provide the basis for smaller-scale microphysical-dynamical feedbacks. Comprehensive observations of key variables both in cloud and in the environment (such as water vapour, temperature, atmospheric dynamics and precipitation) are needed to understand these processes. There are significant challenges in identifying the environmental conditions and feedback processes involved in the transition of cumulus clouds to deep convection and into organized convection such as mesoscale convective clusters.

An assumption for the seeding of mixed-phase convective cloud is that the local aerosol population can influence the overall precipitation by extending the lifetime of storms (Mather et al. 1997). Statistical analysis of satellite data over the tropics by Chakraborty et al. (2016) provides evidence that the lifetime of mesoscale convective systems increases with aerosol loading. The effect is most apparent during the decay phase of these systems. Although this result does not confirm the seeding hypothesis, it does demonstrate that aerosols can influence large-scale storm systems across the globe. It also supports the suggestion by Marinescu et al. (2017) that it is important to observe the vertical profile of aerosol particles, rather than just the surface value.

However, Seifert et al. (2012) use a high-resolution model for a long period study to investigate the sensitivity of warm-season (JJA) precipitation at mid-latitudes (Germany) to aerosol loading (CCN and INP), and they find that owing to the complex interactions between microphysics and dynamics the aerosol effect on precipitation is small when averaged over space and time. Similarly, the diurnal cycle of precipitation shows only small sensitivities to variations in CCN and INP.

## 2.5 Conclusions

In this chapter the main features of the clouds and cloud systems most targeted for precipitation enhancement have been summarized. Our understanding of a number of cloud and precipitation processes has improved in the last two decades, and it is now evident that clouds should be viewed within the synoptic environment, including the thermodynamics and dynamics of the larger-scale atmosphere.

The two main cloud systems of interest for precipitation enhancement are wintertime orographic clouds, generally associated with mid-latitude frontal systems, and convective cloud systems, generally forced by surface heating. In both these cloud systems, there tend to be individual convective cells embedded within a larger mesoscale framework.

While all-liquid processes can lead to precipitation in some clouds, mixed-phase microphysics are important in the development of precipitation in wintertime orographic cloud and in most convective cloud systems identified as suitable for precipitation enhancement. The relationship between cloud condensation nuclei (CCN) and the development of precipitation in warm clouds (with cloud top below the freezing level) is relatively well understood, with high concentrations of CCN tending to delay or suppress the onset of precipitation.

In contrast to the abundance of CCN, the concentration of naturally-occurring ice nucleating particles (INP) is invariably low, leading to supercooled liquid water extending above the freezing level. The complexity of mixed-phase processes means that the relationship between INP and precipitation in these cloud systems is not well known.

- There are substantial uncertainties in the pathways of ice formation from INP. At present, it is not possible to predict the INP concentration, or even the specific ice formation mechanism, in terms of the aerosol concentration and chemistry. There is uncertainty in the spatial and temporal variability of naturally-occurring INP.
  - The relationship between INP and ice particle concentration in mixed-phase cloud is further complicated by the occurrence of ice multiplication processes, which remain poorly understood. The feedbacks between microphysical and dynamical processes in these clouds are also poorly documented and understood.
  - The development of precipitation and the ultimate distribution of precipitation on the ground are determined by feedbacks between boundary layer processes, the cloud microphysics and the dynamics within cloud and associated with the larger-scale flow for both orographic and convective cloud systems. These feedbacks are not well understood. Especially observations of sub-cloud aerosol particles, their activation properties and updrafts are quite important.
  - The detailed development of the diurnal cycle of convective clouds and precipitation, including the role of merging of storm cells, is not well understood.
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### **3. POTENTIAL FOR PRECIPITATION ENHANCEMENT**

#### **3.1 Introduction**

In its 2003 review, National Research Council (2003) concluded that the absence of “convincing scientific proof of the efficacy of weather modification” was due mainly to the “absence of adequate understanding of critical atmospheric processes”. Since that time, there has been progress in our understanding of many of the key atmospheric processes (see Chapter 2). In this chapter, progress on seeding processes is considered, covering such issues as the scientific basis for cloud seeding and the potential to either enhance or suppress precipitation.

Cloud seeding is in most cases a mechanism by which more hydrometeor-forming particles (CCN or INP) are added to the cloud. Any seeding particle added in the cloud formation phase will naturally follow the same laws as the naturally present background aerosol particles. Its activation will depend upon the supersaturation, as well as its size and chemical composition. Depending on its size and composition with respect to the background aerosol particles, it can impose and substitute itself and prevent activation of some of the ambient particles or act as a more effective INP (see Chapter 2). Thus, the resulting number and size of hydrometeors is changed.

Here, we primarily focus on the main cloud systems that are believed to be susceptible to seeding: (1) Winter orographic clouds, where supercooled liquid water (SLW) generated on the upwind slopes of mountain ranges may be transformed into additional precipitation-producing ice crystals via the introduction of seeding material (INPs). (2) Liquid or mixed-phase convective clouds, where liquid phase or the interactions between liquid and ice phase microphysics with seeding material may lead to enhanced precipitation.

Over time, other technologies have been proposed to enhance precipitation from cloud systems. Uncertainties in the scientific basis of technologies such as ionization and sound waves are also considered in this chapter. Finally, there is discussion of the challenge to scale up demonstrations from local cloud to catchment scales with economic benefit to the broader community.

#### **3.2 Winter orographic clouds**

##### **3.2.1 *Physical basis of seeding winter orographic clouds***

It has long been recognized that orographic cloud systems are favourable targets for cloud seeding (Dennis, 1980). Mountain ranges almost invariably are the major source for water catchments and represent the headwaters of major rivers in the world, with precipitation closely aligned with the orography. Winter storms associated with the passage of synoptic fronts provide a regular source of natural precipitation; for example, Chubb et al. (2011) find that about 80 % of wintertime precipitation in the Snowy Mountains of south eastern Australia is associated with the passage of cold fronts. Moreover, provided that the freezing level is below or not too far above the mountain peaks, SLW is naturally generated as cloud rises over the ranges. Key factors determining the amount and depth of the layer of SLW are the wind speed, thermodynamic structure, and the slope of the mountain ranges. Thus winter

orographic cloud systems can provide a regular and geographically fixed source of SLW that can potentially be converted to ice through the introduction of suitable INP (glaciogenic seeding).

The mechanisms through which mountain ranges enhance (or suppress) precipitation are described by Houze (2012) (see Section 2.4.2). Detailed field studies (for example, Warburton and Wetzel, 1992; Geerts et al., 2015; French et al., 2018) and numerical modelling (for example, Watson and Lane, 2014; Xue et al., 2013a) have shown that, provided the freezing level is suitably aligned with the orography, SLW can be generated on the upwind side of mountain ranges. Through natural nucleation and riming, the SLW may be converted to ice as the cloud flows over the ranges. However, the consistent presence of SLW does provide a potential opportunity for the introduction of additional material to promote the conversion of SLW to ice, and hence to enhance precipitation over the ranges. While there is a potential for enhanced precipitation, both observations and modelling suggest that the natural precipitation processes are complex and dependent upon the stability of the flow over a mountain (represented by the Froude number) and by the geometry of the mountain (represented by its aspect ratio).

The cloud processes associated with the enhanced conversion of SLW to ice and hence to precipitation have been followed both in field experiments and through numerical modelling. Super and Heimbach (1988) used an aircraft to track the plume of glaciogenic particles from ground-based generators in the Bridger Range, Montana, USA. They found that, when the plume intersected a region of SLW, the concentration of ice particles was significantly increased. Field studies since that time have documented the microphysical impacts of seeding in more detail.

Geerts et al. (2010) use an aircraft-based W-band Doppler radar to follow the impact of ground-based seeding material (silver iodide) on the microphysics of orographic cloud associated with winter storms as part of the Wyoming Weather Modification Pilot Project (WWMPP, Breed et al., 2014) in USA. The mountain range is about 1500 m above the surrounding plains and about 30 km long, so that it provides a substantial barrier for the flow. During seven flights in similar conditions, 44 unseeded and 70 seeded passes were made along four cross-flow legs downwind of three seeding generators. Most flights were in post-frontal conditions with relatively shallow clouds over the mountain. The Froude number tended to be greater than one, so that flow was over rather than around the mountain. Indicators of seeding impact are found by comparing the radar data from seeded and unseeded flight legs using frequency - altitude displays (FADs), developed by Yuter and Houze (1995). It is shown that there is a 25% increase in snowfall in the boundary layer during seeding based on radar reflectivity, and that the seeding signature increases with Froude number, that is with decreasing stability. Further analysis of these data by Miao and Geerts (2013) suggests that the seeding signature is largest within the boundary layer over the high terrain above cloud base, and that it is not apparent in the lee of the ranges. These results were based on radar derived reflectivity measurements that not necessarily indicate similar precipitation increases at the surface.

Pokharel et al. (2014) describe the 2012 AgI Seeding Cloud Impact Investigation (ASCII-12) field campaign, which was also carried out as part of WWMPP in Wyoming. The detailed design of the campaign is given in Geerts et al. (2013). Three distinct radars were used: an aircraft-

based W-band radar, a pair of Ka-band microwave rain radars, and an X-band Doppler radar. The three radar systems consistently found an increase in reflectivity in the boundary layer in seeded conditions in the target area, and confirmed the earlier results of Geerts et al. (2010).

A recent field effort as part of the Idaho Power SNOWIE project in the State of Idaho, for the first time documented the complete chain of ice nucleation to crystal and precipitation formation down to the surface using combined in situ aircraft and surface based radar measurements and in situ airborne instruments (French et al., 2018). The complete chain of microphysical events from seeding to snow descending to surface was documented for a case study. Seeding in this case was done upwind from the peak of the mountains using silver iodide flares directly injected into the supercooled region of the cloud. These studies demonstrate that, under the right conditions, seeding can lead to an increase in radar reflectivity and hence to an increase in snowfall rate. They provide a scientific basis for any measured increase in precipitation on the ground associated with seeding.

Morrison et al. (2013) has demonstrated the value of utilizing satellite observations to identify potential regions for glaciogenic cloud seeding/weather modification. By utilizing the MODIS instrument on the Terra and Aqua platforms and level-2 (processed) products of cloud-top temperature (CTT) and cloud-top phase (CTP), a climatology comprising the absolute frequency of occurrence of supercooled cloud tops has been conducted. The analysis was focused on locations where glaciogenic cloud seeding has taken place in south eastern Australia and Tasmania and in the western United States. The climatologies illustrate the differences between the two regions with respect to the presence of supercooled liquid water.

The optimal conditions for seeding over mid-latitudes during the wintertime seem to be: (1) there is the right alignment of freezing level height with the mountain height, in order to enable significant formation of supercooled water on the upwind side, and (2) cloud top temperature is between  $-10^{\circ}\text{C}$  to  $-25^{\circ}\text{C}$  (Cotton and Pielke, 2007). The geographic regions in the mid-latitudes that support those conditions during the winter are mountains where their tops are in the range of 1000 to 3500 m, and when the freezing level is located between 1-3 km (Reynolds and Dennis, 1986; Mooney and Lunn, 1969; Kim et al., 2016). The optimal synoptic conditions should enable moist flow over the mountains, with neutral or conditionally unstable conditions (above a certain level) to support the formation of orographic clouds. Such suitable conditions may be found in the post-frontal sectors of mid-latitude cyclones.

Thus, field studies over the last decade have shown that both aircraft-based and ground-based glaciogenic seeding lead to clear signatures of a seeding impact on cloud microphysics and those changes are associated with enhanced precipitation based on radar measurements. Model simulations have confirmed this finding (for details see Chapter 5). Such evidence of seeding impact must be accompanied by evidence of increased precipitation on the ground for a precipitation enhancement project to be described as fully successful.

Given the high variability of natural precipitation at the ground, it is difficult to demonstrate enhanced surface precipitation in a specific case study: careful statistical analysis is needed to demonstrate such increases over many experimental units and over a larger area. In addition, there is some observational evidence of changes in microphysical properties of ice particles at the surface associated with seeding and it is unclear how this will impact the overall precipitation amount increase.

### **3.2.2 Seeding strategies**

Seeding material can be dispersed into clouds from aircraft, artillery shells and small-sized rockets, special high-altitude fireworks (ejected up to 200 m in the atmosphere) or from ground-based generators. The most common seeding material is silver iodide, which will nucleate ice particles at temperatures below about  $-5^{\circ}\text{C}$ . Dennis (1980) gives details on the design and behaviour of silver iodide (AgI) generators, in which AgI is vaporized in an acetone-based flame. Other chemicals are usually added, because AgI is insoluble in acetone. In fact, Feng and Finnegan (1989) show that the nucleating properties of AgI can be enhanced with the addition of sodium chloride (common salt); this material is used for cloud seeding in the Snowy Mountains of south eastern Australia (Huggins et al. 2008) and central Wyoming (Breed et al. 2014).

Aircraft are used in many projects to directly disperse the seeding material in supercooled regions of the winter orographic clouds. Due of the risks associated with carrying inflammable liquids on aircraft, pyrotechnic flares have been developed for aircraft-based seeding (Dennis, 1980).

In recent years, new formulations of seeding material are being developed for release from pyrotechnic flares (National Research Council, 2003). These materials require less AgI than older formulations, and they are much more active in ice nucleation at temperatures colder than about  $-5^{\circ}\text{C}$ . Considerable work to improve the efficiency of seeding materials is being carried out by numerous groups using complex chemical compositions, nanotechnologies, different types of cloud chambers and full-size testing stands of seeding devices (Zou et al., 2017, Drofa et al., 2010 and 2013).

Silver iodide is not the only material used to seed clouds. Indeed the earliest experiments on cloud seeding used pellets of dry ice (solid carbon dioxide) dropped from aircraft (Dennis 1980). Dry ice pellets have a surface temperature of around  $-78^{\circ}\text{C}$ , and so they freeze any cloud droplets on their paths and they also activate cloud condensation nuclei to form droplets that freeze through homogeneous nucleation. In addition, liquid carbon dioxide sprayed from an aircraft or surface based liquid propane burners have been used. Seto et al. (2011) found a radar signal due to seeding with liquid carbon dioxide sprayed from an aircraft, and they showed that the impact could be simulated in a numerical model. Similar effects can be obtained using liquid propane, which can be dispersed from ground generators (Super and Holroyd, 1997). Bakhanova and Leskov (2015) in special flight experiments obtained higher crystallization efficiency for porous charcoal or aerosol granules impregnated with liquid nitrogen than seeding with solid carbon dioxide granules. It should be noted that these seeding materials act locally and dissipate with time due to thermodynamics and mixing, while AgI is persistent and can be transported into other clouds and become effective at much later times and greater distances. On the other hand, the INP capability of AgI particles is gradually reduced by solar radiation and (more slowly) by dissolution in water drops. Analysing the process of ageing of INP based on AgI over time due to influence of high humidity and UV-radiation, Shilin et al. (2015) conclude that a considerable decrease of ice-forming efficiency occurs only when soluble iodide compounds are present in the INP. Otherwise, such changes are insignificant. It was suggested that the main reason of ageing is recrystallization of seeding material.

Given the variability of operating conditions, it is important to ensure that seeding generators produce a steady flow of seeding material and that the particle size distribution and number and mass concentrations of the seeding material is documented (Huggins et al., 2008). These precautions are needed to ensure that any seeding effects can be related accurately to the source characteristics. It is also vital to ensure that the plumes from generators are dispersed into regions of cloud where they can interact with any available SLW. The targeting and dispersion of seeding material remains an important issue in seeding experiments and need to be validated by observations and numerical model simulations (Super and Heimbach, 1988; Bruintjes et al., 1995, Xue et al., 2013a, and French et al., 2018 amongst others). Routine targeting is achieved through the use of a suitable model, which can vary from rather simple dispersion-microphysical models to full three-dimensional numerical models (see also Chapter 5). For wintertime orographic cloud, Huggins et al. (2008) use snow chemistry analysis to demonstrate that the simple model of Rauber et al. (1988) is able to adequately target seeding material from ground-based generators, and Manton et al. (2011) use that model for targeting in the Snowy Precipitation Enhancement Research Project (SPERP). The advances in three-dimensional modelling allow Breed et al. (2014) to use back-trajectories from the WRF model to optimize the location of ground generators for the WWMPP.

A cloud seeding parameterization in a two-dimensional version of the Weather Research and Forecasting (WRF) model is used by Xue et al. (2013a) to suggest that the effects of aircraft-based and ground-based seeding are different. For aircraft-based seeding, where the seeding material is dispersed directly into regions of SLW, deposition of water vapour onto the introduced ice nuclei is the main mechanism for the growth of ice particles. However, for ground-based seeding, where the seeding material must be mixed vertically into the SLW region, the dominant effect is probably from AgI acting as CCN when temperatures are warmer and subsequent immersion freezing, as the introduced ice nuclei are incorporated into the SLW droplets before freezing occurs. Three-dimensional modelling by Xue et al. (2013b) confirms that in general direct and near cloud methods of clouds seeding are more efficient. Xue et al. (2013a, 2013b) also find that the seeding impact tends to increase with the flux of seeding material in some situations.

### **3.2.3 Snow chemistry**

Warburton et al. (1995) made trace chemistry observations of silver in snow during cloud seeding experiments in USA. The observed data, which are collected in real time during seeding events and later carefully analysed in a clean laboratory, help determine whether the seeding material from ground-based generators is well targeted. Manton et al. (2011) use such snow chemistry observations to optimize the configuration of the simple dispersion model (Rauber et al., 1988) used for targeting in the Snowy Precipitation Enhancement Research Project (SPERP), and Manton and Warren (2011) show that there is a significant difference between the maximum concentration of silver in the target area in seeded and unseeded events, taking the difference as a primary indicator of targeting the seeding material in SPERP.

While snow chemistry can be valuable in identifying the effectiveness of targeting of seeding material, Chai et al. (1993) show that it can even be useful in identifying whether seeding has led to changes in the microphysics of the precipitation process. The technique requires the use of two generators at each dispersion site: one generator disperses silver iodide in seeded events and the other disperses indium oxide in both seeded and unseeded events. The silver

and indium particles have similar aerodynamic properties, but indium oxide does not nucleate ice. In the absence of any microphysical effects, both silver and indium will reach the surface in snow due only to scavenging of the aerosols by cloud particles. However, if AgI particles lead to an increased number of ice crystals in cloud, then the concentration of silver in snow on the ground should be considerably higher than that of indium. Chai et al. (1993) found silver to indium ratios of more than 17 in seeded conditions at Lake Almanor, California, USA, confirming that seeding has had an impact on the cloud microphysics. In SPERP, Manton and Warren (2011) found a significant difference of the ratio of silver to indium between seeded (median 3.0) and unseeded (median 0.3) events similar to what was found in the previous experiments.

Xue et al. (2017) use the WRF model at 667-m resolution to simulate two ground-based and two aircraft-based cloud seeding events in Idaho, USA, when indium oxide was released with the seeding material (silver iodide). They found that the model is able to accurately simulate the dispersion of seeding material. They also found that aircraft-based seeding is much more efficient than ground-based seeding, due to the silver iodide being directly injected into SLW regions of the cloud at higher altitudes. Earlier modelling studies by Levin et al. (1997) also find that the effectiveness of ground-based seeding can be limited by seeding material not reaching the regions of SLW.

### **3.3 Convective and stratiform cloud systems**

Precipitation formation in convective clouds proceeds by either condensation-collision-coalescence process at warmer temperatures or through the ice formation and mixed phase processes at colder temperatures. Mixed-phase processes dominate typically in continental and deep tropical convection with complex microphysical processes in mixed phase regions (Rosenfeld and Lensky, 1998; Xu and Zipser, 2012) and can be significantly altered by different concentrations of aerosol particles (Andreae et al., 2004; Grabowski and Morrison, 2016). They found that typically, large aerosol number concentrations in small sizes lead to an increase in the small droplets, compared to low aerosol number concentrations where few larger drops are formed during the early development stages of the cloud (see Chapter 2). As the cloud develops and grows above freezing level, mixed phase processes become important in contributing to precipitation formation but the evolution of the mixed-phase processes is highly dependent on the liquid phase processes (Lawson et al., 2016).

The relationship between CCN/INP and raindrop/ice number concentrations is determined by several microphysical processes and their interactions (see Chapter 2). It is also possible that low aerosol concentrations result in larger-sized droplets in the initial stages of cloud development (Khain et al., 2001, 2005) that are lifted above the freezing level in strong updrafts, resulting in an ice multiplication process associated with significantly higher observed ice number concentrations compared to the primary INP concentrations (Lawson et al., 2016; Field et al., 2017). The splintering of the larger freezing drops introduces a large number of small ice crystals that subsequently grow and produce the majority of the raindrops on their passage across the freezing level. In high aerosol conditions, small droplets are lofted above the freezing level and it may be possible that ice multiplication processes are less efficient. However, during the monsoon conditions over India, it was found that ice multiplication processes may be efficient for precipitation formation (Patade et al., 2016; Gayatri et al.,

2017) while large numbers of aerosols are present in a moist environment with cloud bases at warmer temperatures ( $>15^{\circ}\text{C}$ ) producing a deep liquid region in the cloud.

Observations of supercooled liquid in clouds are reported in several studies. Heymsfield et al. (1979) report that undiluted updraft cores with small supercooled drops exist up to  $-18.8^{\circ}\text{C}$  in mid-latitude cumuli, and mid-latitude continental clouds with colder bases ( $<+10^{\circ}\text{C}$ ) do not develop large supercooled drops (Cannon et al., 1974; Heymsfield et al., 1979; Dye et al., 1974, 1986; Lawson et al., 2014). Rosenfeld and Woodley (2000) report up to  $1.8\text{ g/m}^3$  liquid water at  $-37.5^{\circ}\text{C}$  in vigorous cumulus over west Texas. Lawson and Gettelman (2014) reported observations of  $0.7\text{ gm}^{-3}$  of supercooled LWC at  $-35.5^{\circ}\text{C}$  in a mostly isolated, relatively small towering cumulus. SLW has also been recorded in deep cumulus clouds over Indian continent with high CCN at the cloud base (Prabha et al., 2011; Gayatri et al., 2017). Several studies documented that an increase in aerosol concentration can increase the cloud droplet concentration and supercooled liquid at high levels (Freud et al., 2008; Khain, 2009; Prabha et al., 2011; Tao et al., 2012; Khain et al., 2013, 2015). Enhanced supercooled liquid water has an effect on homogeneous freezing and riming, as well as several microphysical processes leading to precipitation (Khain et al., 2011; Ilotoviz et al., 2016). With a warm cloud base ( $>+15^{\circ}\text{C}$ ), and with broad drop size spectra, the updraft cores in the cloud may contain large supercooled drops. Lawson et al. (2015) indicate that secondary ice production by freezing of raindrops and ice splinters is a dominant mechanism in these types of clouds.

Deep convective clouds (DCCs) are more complex and they occur in tropical to subtropical regions (Houze et al., 2015). Aerosol particle impacts in deep convective clouds have been reviewed in several recent works (Tao et al., 2012; Altaratz et al., 2014; Rosenfeld et al., 2014, Fan et al., 2016), and they tend to be dominated by effects of dynamics, thermodynamics, and microphysics. The warm rain may be suppressed by aerosol particles and more cloud liquid water may be lifted above the freezing level, introducing greater latent heat, invigorating convection (Rosenfeld et al., 2008). Pincus and Baker (1994) showed invigoration due to enhanced entrainment induced by faster evaporation. Observational studies indicated enhancement in cloud-top height and cloud cover (Andreae et al., 2004; Koren et al., 2010; Niu and Li, 2012), which was investigated with numerical models (Fan et al., 2013) indicating a microphysical invigoration mechanism induced by reduced ice particle size and fall velocity.

Aerosol particle impacts on mesoscale convective clusters have not yet been established. Thermodynamic invigoration may be active while favourable environmental conditions such as a warm cloud base, a weak wind shear and high CAPE, as well as freezing of extra cloud water, occur. In certain studies, relating to INP, intensification of updrafts was due to latent heat release from ice crystal depositional growth (Ekman et al., 2007). Dust aerosols interact with tropical convective clouds due to the capability of dust particles to act as giant CCN as well as INP to make changes in the mixed phase clouds (Li and Min, 2010; Levin et al., 1996; Semenuik et al., 2015).

Changes in precipitation due to aerosol particles have been emphasised by various studies (Tao et al., 2012; Teller and Levin 2006; Wang, 2005). However, the impact on precipitation over a large area is significantly less due to buffering effects from microphysics or dynamics (Stevens and Feingold, 2009; Fan et al., 2013; Gayatri et al., 2017). These aerosol effects will have to be considered in cloud seeding experiments by taking also into account how the

seeding material will be competing with the background aerosol in cloud and precipitation forming processes.

Aerosol-cloud interactions vary in different cloud types, which introduces additional uncertainties. Aerosol-cloud precipitation interactions also depend on the stage of cloud evolution, as well as the transport and dispersion of seeding material. In spite of progress made in the overall fundamental understanding from observations and numerical simulations (Tao et al., 2012; Lee et al., 2014; Rosenfeld et al., 2014; Khain et al., 2015), interaction between the microphysics and dynamics (Altaratz et al., 2014; Grabowski et al. 2014; Moser and Lasher-Trapp, 2017) remains uncertain (compare Chapter 2).

### **3.3.1 Physical basis of seeding convective cloud systems**

Seeding attempts on mixed-phase convective clouds can be divided into two categories. A glaciogenic seeding introduces INP into the cloud in an effort to enhance the ice/mixed phase of the cloud and subsequent freezing of drops should trigger precipitation. Hygroscopic seeding, however, introduces CCN to enhance the formation of larger drops and activate coalescence process to initiate precipitation.

#### *3.3.1.1 Hygroscopic seeding*

Hygroscopic seeding is potentially applicable to all clouds that have a liquid region close to their base. Hygroscopic material is dispersed into the updraft region at cloud base with an aircraft or from a ground based emitter. Typically, seeding particles are larger and more hygroscopic than the natural aerosol particles. The resulting droplets grow to larger-than-normal sizes through condensation, and then rapidly grow further through collision with other droplets (Cooper et al., 1997; WMO, 2000), initiating the rain process within the convective cell. There are two main concepts under consideration in regard to hygroscopic seeding: the competition effect and the tail effect (Segal et al., 2007).

Results from the South African, Mexican and Australian experiments (NRC, 2003; WMO, 2000; Mather et al., 1997; Silverman, 2003; Tessendorf et al., 2015) indicated that hygroscopic seeding at cloud base early in cloud development might increase the rainfall from continental storms. Indian cloud seeding experiment (Murty et al., 2000) confirmed that the seeded clouds have an advantage in the initial development of precipitation-size drops, complying with the seeding hypothesis. Southeast Queensland (Tessendorf et al., 2015) and India (Prabha et al., 2011) experiments have shown that the efficiency of liquid rain and mixed phase processes varies, and is possibly dependent on other atmospheric factors (such as cloud base height) or background aerosol population. All the experiments illustrated that understanding and documenting the physical chain of events (microphysical and dynamical responses) remain an important step toward acceptance of the statistical results. Sinkevich and Krauss (2013) analysed the development of three cumulonimbus clouds seeded with silver iodide in Saudi Arabia. Continuous satellite and radar observations of the clouds during a five-hour period showed a vertical development of clouds after seeding as well as the increase in the radar reflectivity and potentially precipitation. Yao (2006) gives a review of rain enhancement campaigns of mixed phase convective and stratiform clouds across all seasons in China.

### 3.3.1.2 *Glaciogenic seeding*

For glaciogenic seeding, silver iodide and dry ice are still the most widely used cloud-seeding materials. Both materials enhance the ice crystal concentrations in clouds by either nucleating new crystals or freezing cloud droplets. Based on past experiments, two seeding concepts have been proposed, namely the "static" and "dynamic" seeding concepts (Braham, 1986). While the first attempts to increase precipitation embryos the latter attempts to increase the buoyancy in the cloud by the release of latent heat due to freezing of supercooled liquid drops (NRC, 2003). These experiments and results have been extensively described in the literature (NRC, 2003) but remain inconclusive. As increasing the precipitation embryos will also affect the dynamics of the cloud, the distinction between "static" and "dynamic" seeding may be meaningless, highlighting the overall uncertainty in the effects of seeding.

## 3.3.2 **Seeding strategies**

### 3.3.2.1 *Seeding methods*

Since its inception, the term "hygroscopic seeding" has taken on slightly different meanings depending on the experimental design, type of seeding material used, and the type of cloud that was the subject for experimentation. In all instances the ultimate goal has been to enhance rainfall by somehow promoting the coalescence process. The direct introduction of "appropriately" sized CCN that can act as artificial rain drop embryos using either water sprays, dilute saline solutions, or grinded salts, are the most common hygroscopic seeding techniques used previously (Murty et al., 2000). Although this technique is widely used in countries in Southeast Asia, the previous statistical experiments were generally inconclusive, although some suggested positive effects. Observations and modelling results have lent some support that under certain conditions with an optimal seed drop-size (artificial embryos) spectrum, precipitation may be enhanced in some clouds.

More recently, hygroscopic seeding involves seeding summertime convective clouds below cloud base with pyrotechnic flares that produce small salt particles (about 0.5  $\mu\text{m}$  diameter) in an attempt to broaden the cloud droplet spectrum and accelerate the coalescence process. The burning flares provide larger CCN ( $>0.3 \mu\text{m}$  diameter) to the growing cloud, influencing the initial condensation process and allowing fewer background CCN to activate to cloud droplets (see Chapter 2).

The overall objective during cloud seeding is, thus, that the hygroscopic nuclei dispersed at the cloud base produce larger cloud droplets than present otherwise in a developing cloud, leading to early collision coalescence, accelerating rain formation, influenced by the initial cloud droplet population. Consequently, the hygroscopic flares should provide larger CCN than naturally available which are supposed to activate at lower supersaturations, condense water more readily and limit the total number of droplets activated. As was already discussed in Chapter 2, the number concentration of the background aerosol population needs, however, to be taken into account (Semenuik et al., 2015). In hygroscopic seeding, coalescence of water droplets is promoted to improve the efficiency of rain formation, increasing the number of large drops, i.e. the tail of the drop size distribution (tail effect). Cloud droplets should nucleate preferentially on the seeding particles and this inhibits smaller natural CCN from activation (see Chapter 2), resulting in a broader-than-natural droplet spectrum near cloud base triggering collision-

coalescence within 15 minutes (Cooper et al., 1997) and initiating the rain process earlier within a typical cumulus cloud lifetime of 30 minutes. This is expected to increase the potential for precipitation to develop earlier and more efficiently in the lifetime of the cloud.

A second seeding strategy for convective clouds relies on the use of glaciogenic seeding agents. Introducing those agents close to cloud base will yield an effect similar to hygroscopic seeding as the AgI particles are large enough (mean size of 0.1mm; Dessens et al., 2016) to serve also as CCN. Reaching higher altitudes, the IN will freeze the supercooled liquid water drops and trigger precipitation via the formation of graupel particles. Depending on the height of the freezing level the particles will melt before reaching the ground. Artillery shells (Zhekamukhov and Abshaev, 2012) and anti-hail rockets (Abshaev et al., 2006) are widely used to deliver glaciogenic seeding materials directly to a specific altitude for convective clouds in the required dosage. Thus, it can be expected for these cases that deposition and contact freezing would be the dominant processes.

Dispersed from sub-cloud and cloud top levels or directly into regions of SLW, deposition of water vapour onto the introduced ice nuclei is supposed to be the main mechanism for the growth of ice particles. As the direct penetration of the SLW is dangerous for aviation, for the majority of aircraft-based seedings of convective clouds the release of seeding materials is realized from sub cloud or cloud top levels. Applying this seeding strategy one has to account for the time required for the seeding material to attain the given level of SLW in the cloud, which can range from several to tens of minutes.

#### 3.3.2.2 *Seeding materials*

Hygroscopic seeding in convective clouds is carried out with the help of aircraft based flares or the dispersing of micropowders. Either pulverized salt or pyrotechnic flares are used. For producing small hygroscopic particles, calcium chloride and/or other salts are burned from racks mounted on an aircraft wing. Conceptual designs to dispense sea spray like giant aerosol particles from light-weight artillery shells has also been discussed (Ghosh et al., 2016) for hygroscopic seeding.

The principle of hygroscopic flare seeding is to have the flares produce effective CCN (usually salts such as sodium chloride, potassium chloride, or calcium chloride) particles in larger sizes (large or giant nuclei) than occur in the natural environment. The chemistry (hygroscopicity), size and concentrations of the particles (CCN) produced from the flares or large particle salt seeding needs to be evaluated. The flares are fitted in the racks attached to the wings of the aircraft inside cardboard container 12 cm long 7 cm diameter (Bruitjes et al., 2012). Hygroscopic flares contain sodium chloride or calcium chloride and produce small salt particles in the size range 0.1-10  $\mu\text{m}$  diameter.

Cooper et al. (1997) find that an optimum particle size of 1  $\mu\text{m}$  is required in order to form drizzle drops and to enhance collision coalescence process. The optimum size of soluble particles was found to be 1-5  $\mu\text{m}$  (Reisin et al., 1996; Yin et al., 2000a; WMO, 2000; Caro et al., 2002; Segal et al., 2004; Rosenfeld et al., 2010). It is important to have information also on the sub-cloud aerosol particle size distribution recognising that, if close to the coastline, it can be dominated by already large sea salt aerosols.

Drofa et al. (2010, 2013) studied the effect of seeding of a cloudy environment with salt powder in a big cloud chamber (3200 m<sup>3</sup>) and then in a 2-D warm cloud model. The experiments were carried out in a cloud chamber in conditions corresponding to the formation of convective clouds. The results showed that the introduction of the salt powder before a cloud is formed in the chamber results in the formation of a "tail" of additional large drops. In this case, seeding with the salt powder leads also to an increase in size of the entire population of cloud drops and to a decrease of their total concentration as compared to a cloud that is formed on background aerosols. Thus, the experimental data and the results of numerical simulations showed that a salt powder milled to a size of several  $\mu\text{m}$  is more effective in initiating warm rain than hygroscopic flares. Dispersion of such quantities is not feasible with hygroscopic flares, but the quantity is practical with salt powder (Rosenfeld et al., 2010). While the chamber experiments and numerical model simulations provide some evidence of the effects of salt powder seeding, their validation in the real atmosphere is necessary as their potential increases in precipitation are unclear. Belyaeva et al. (2013) showed with numerical simulations that use of polydisperse salt powders has advantage over hygroscopic reagents from pyrotechnic flares and that precipitation could be induced from warm convective clouds of moderate thickness that did not precipitate naturally.

Zhekamukhov and Abshaev (Parts 1-2; 2009) showed that anti-hail rockets equipped with hygroscopic micro-powders could be effectively used for seeding the cores of cumulus and cumulonimbus clouds for the purpose of precipitation enhancement. The optimum suggested size of NaCl crystals is 7.5-10  $\mu\text{m}$  as these "salty" droplets can rapidly grow to raindrops size through condensation - coalescence mechanisms.

Silver iodide nuclei dispensers either burn a solution of silver iodide in acetone, or pyrotechnic flares (ejectable or burn-in place, both are used in convective clouds). The silver iodide acetone solution is forced through the nozzle into a combustion chamber where the atomized solution is ignited, and the silver iodide crystals formed through combustion are expelled along with the other combustion by-products into the atmosphere (ASCE 2004; Griffith, 2006). For flares, AgIO<sub>3</sub> is used as it provides necessary oxygen to burn the flare.

Silver iodide can be dispersed either by pyrotechnic flares from generators at the surface or in the air. In the ejectable flare, it is ignited as it leaves the aircraft and falls 600-1,800 m (depending on the designed burn time). Pyrotechnic flares typically produce 10 to 100 g of active seeding agent per minute of burn, whereas aerial acetone generators typically produce 2 to 3 g of active seeding agent per minute. In a number of projects pyrotechnic cartridges (or flares) are used to deliver silver iodide particles from the top of convective clouds (Koloskov et al., 2010; Krauss and Santos, 2004 and others).

Dry ice is also used and is dispensed through openings located through the floor of baggage compartments of cloud seeding aircraft. Dispensers disperse pelletized (diameters of 0.6 to 1 cm and 0.6 to 2.5 cm) or small particles of dry ice. Mountain Valley Sunshine project in Utah, USA (Fukuta, 1996) used liquid carbon dioxide for shallow clouds and supercooled clouds. The type of seeding agent and dispensing mechanism will determine which type of device (aircraft, rocket, etc.) should be used for the seeding. Hygroscopic seeding is usually dispensed from aircraft near cloud base through flares or salt powders. The dry ice and ejectable flares are used for cloud top application using aircraft. Rockets and artillery shells are used for direct and almost simultaneous seeding of AgI in the supercooled part of the cloud in

necessary dosage, even in the conditions of severe turbulence and lightning activity. Ground based systems are applied with generators and pyrotechnic flares of AgI.

As already mentioned, the effectiveness of seeding will depend on the natural background particles and their characteristics with regard to the seed particles. Dust particles can act as CCN and also as INP and the seeding potential of the clouds is to be evaluated with respect to the information on dust particle concentration in the sub-cloud layer. Also elevated layers of aerosol particles can be present in the atmosphere, which are to be considered. The presence of dust particles or aggregates present in ambient air may be detrimental for the coarse particle seeding as they can act as giant CCN. Dust aggregates with various organic species adsorbed on their surfaces were noted by Falkovich et al. (2004). In UAE for e.g. dust particles combined with sulfates and NaCl were found (Semeniuk et al., 2014) and they can form giant CCN as reported by Levin et al. (1996). As they demonstrated, from TEM analyses of samples collected, both inorganic and organic species may be present on a single mineral particle.

New types of cloud-seeding materials synthesized on the basis of nanotechnologies as a promising water-augmentation technology has drawn attention. Recently, Tai et al. (2017) designed and synthesized a type of core/shell NaCl/TiO<sub>2</sub> (CSNT) particle with controlled particle size, which successfully adsorbed more water vapour (~295 times at low relative humidity, 20% RH) than that of pure NaCl, deliquesced at a lower environmental RH of 62-66% than the hygroscopic point (hg.p., 75% RH) of NaCl, and formed larger water droplets ~6-10 times its original measured size area, whereas the pure NaCl still remained as a crystal at the same conditions.

### 3.3.2.3 *Transport and dispersion*

Cloud seeding criteria used in typical experiments are mostly visual criteria applied by pilots such as solid cloud base with 1-2 ms<sup>-1</sup> updraft, growing cloud turrets, etc. Aircraft usually conducts passes below cloud base to monitor the updraft areas and aerosol particle and CCN concentration. Sometimes aircrafts also climb to a higher altitude to identify the actively growing clouds. The criteria considered include liquid water content near cloud base or at higher altitudes to determine seeding potential. Once updrafts are identified at cloud base seeding commences. Up to three seeding events are generally conducted per flight. For glaciogenic seeding at higher altitudes silver iodide flares are used and dispersed directly into the supercooled liquid water regions.

The dispersion and transport of seeding material has been the topic of much study in the past. Cooper et al. (1997) suggested that for hygroscopic seeding the main mechanism for dispersing the seeding effects throughout the cloud may be through the formation of drizzle drops that would mix through the cloud when reaching cloud top. Several tracer studies have also been conducted (see next section) to study this aspect.

Use of sophisticated numerical models such as Xue et al. (2016) have also studied these aspects. Segal et al. (2004) showed that submicron particles can actually suppress warm rain formation. Introduction of large hygroscopic particles produced raindrops more quickly. However, if too few large particles are present then there may be a smaller number of raindrops. Such numerical experiments can be conducted prior to the seeding experiment with knowledge of background data on aerosol size distribution. Levin et al. (1996) showed that in

the Israeli experiments when seeding is done in lines in front of the approaching convective bands very little of the seeding material reaches the appropriate regions of the cloud. Belyaeva et al. (2013) showed with numerical simulations that use of polydisperse salt powders has advantage over hygroscopic reagents from pyrotechnic flares and that precipitation could be induced from warm convective clouds of moderate thickness that did not precipitate naturally.

The advances in technology (compare Chapter 4) provide a new dimension to the targeting and evaluation of cloud seeding experiments. Radar polarimetric parameters can be used to find the zones of hydrometeor classes (e.g. Z<sub>d</sub>R) that may be targeted with more precision and may help with the selection of areas for seeding. High quality real-time radar observations illustrating different types of hydrometer and other analysis products from dual polarization radar networks in the world seem to have a large potential for targeting and evaluation for cloud seeding experiments.

The new generation of geostationary satellites enables tracking of clouds at higher resolutions, and so cloud top and other spatial structures will be discernible. Information on cloud types and microphysics during potential seeding days especially the relationship between cloud top temperature and effective radius (Rosenfeld and Lensky, 1998) together with estimates of vertical velocity and CCN information (Rosenfeld et al., 2014) could be derived. This information together with sophisticated numerical modelling gives proper guidance in the seeding decisions.

Optimal seeding conditions may be determined based on guidance from the high-resolution weather forecast radar visualization using improved analysis tools (such as TITAN, ASU-MRL, etc.) that can handle the selection of variable target/control areas or individual radar cells (Woodley et al., 2003a, b; Woodley and Rosenfeld, 2004; Abshaev and Zharashuev, 2010). Knowledge of the climatology of aerosol, clouds, and precipitation related parameters (radar observed fields that characterize cloud seedability) are essential for the design and execution of cloud seeding experiments.

When ground-based generators are used, the number of generators and spacing between them, the distance upwind of the target, wind conditions, cloud base temperature, transport and dispersion of the seeded material etc. need to be given careful consideration. The cloud seeding programme should determine the transport, dispersion and dilution of seeding agent in the clouds. Past experiments have illustrated that knowledge about delivering seeding material in right quantities at the right time in the clouds is limited. Temperature range, type of cloud, delivery mechanism (ground or airborne) and seeding targets are all crucial factors to be considered. Advanced technologies with unmanned aircraft (UAV) to target clouds and carry out seeding show future potential in some situations (DeFelice and Axisa, 2016).

#### 3.3.2.4 *Tracer releases*

A tracer (chaff and/or SF<sub>6</sub> released from an aircraft or at the surface) can be used as a tag for a seeded region for understanding the dispersion and transport of the seeding material. The dispersion and transport of the chaff (Reinking and Martner, 1995) can be monitored by radar while the detection of the SF<sub>6</sub> is done with an aircraft (Rosenfeld et al., 2010) equipped to

detect this gas at very low concentrations. These methods illustrate the usefulness in examining the seeding hypothesis and to demonstrate the potential efficacy of cloud seeding. Scientific evaluation of the seeded cloud volume has been attempted by releasing tracers along with the seeding material and tracking their signature within convective clouds. SF<sub>6</sub> tracers have been used by Rosenfeld et al. (2010) for identifying seeding signature in convective clouds over Texas, USA. They failed to get a seeding signature while using hygroscopic flares with SF<sub>6</sub> tracer. They have also used salt powder with diameters 2-5 µm as a seeding agent to promote drizzle and further raindrop formation. Although microphysical effects were illustrated and the seeded volume was verified with the SF<sub>6</sub> tracer, they argued microphysical processes could vary under different environmental conditions. It is also emphasised that additional investigations both with numerical simulations and observations with flare and salt seeding are necessary.

Studies of the transport and dispersion of seeding material in convective cloud modification experiments were conducted in Moldova for twenty consecutive summer seasons. In the course of the experiments, special tracers based on deuterium 210Po and D2O (Shalavejus, 1996; Shalavejus and Dinevich, 1995; Dinevich and Shalaveyus, 2010) were inserted into different cloud cells by means of rockets and, in some cases, aircraft. A dual-wavelength weather radar (MRL-5) was used for measuring cloud structure, movement direction and velocity. Rain gauges and special laboratory equipment were used for the detection of tracers in precipitation on the ground.

### **3.4 Redistribution and “negative enhancement” of precipitation**

The areas affected by cloud seeding remain an open question especially with regard to cloud seeding of convective systems. Related uncertainties pertain to the issue of “extra-area” effects, that is, whether seeding can affect the weather beyond the targeted temporal or spatial range. The persistent effects of cloud seeding claimed by Bigg (1995) should be carefully assessed, as should the statistical results from experiments in Thailand (Silverman and Sukarnjanasat, 2000; Woodley et al., 2003b) and Israel (Brier et al., 1973), which claim effects beyond a few hours. Some argue that increasing precipitation in one region could reduce precipitation downwind (by “stealing” the atmospheric water vapour); for example, recent modelling studies by Geresdi et al. (2017) suggest that in some circumstances there may be a decrease in precipitation on the lee side of a mountain, even when there is an overall increase over the whole domain. On the other hand, analysis of Long (2001) suggests that enhanced downwind precipitation may be promoted by the transport of ice nuclei or ice crystals or by the dynamic invigoration of clouds through the release of latent heat. Overall, further quantitative studies are needed to resolve these issues, bearing in mind the uncertainties in assessing the impact of seeding in a designated target area.

Around the world, weather modification technology has been utilized not only for rain enhancement, but also for hail suppression, fog clearing and rainfall intensity reduction. There are also attempts of some countries, such as Russia and China, to apply weather modification technology to prevent rain occurrence during important local events at specific sites. As for rainfall intensity reduction, the same physical considerations apply as for precipitation enhancement: a documented success will add credibility to the overall cloud-seeding concepts.

Givati and Rosenfeld (2004) suggest that urban air pollution in California and Israel may reduce annual rainfall by about 15-25%. According to Khain et al. (2005), small CCN may produce small droplets, which have small collision efficiency, thereby reducing precipitation from deep convective clouds. Introducing super-fine hygroscopic seeding agent into the clouds would then initiate the formation of small droplets that compete with existing cloud droplets in the water vapour absorption process within the cloud. This method may prevent the development of precipitation in some cases.

On the other hand, as was already discussed above, introducing giant hygroscopic seeding agents into clouds can increase the collision efficiency of droplets and lead to the rapid development of rain (Silverman and Sukarjat, 2000). This mechanism can be applied to developing upwind clouds with the potential to produce rain over a substantial target area. This "jumping process mechanism" will then reduce the potential of the cloud to develop rain over a target area.

During the last thirty years considerable work has been done in Russia on precipitation redistribution above megalopolises and neighbouring areas. More than 80 projects have been completed during national days (Dovgaljuk et al., 1998; Dovgaluk et al., 2010; Koloskov et al., 2011; Koloskov et al., 2010), with different (cold and warm) types of clouds and cloud systems (stratus and convective) being seeded by 6 to 12 aircraft dispersing silver iodide, liquid nitrogen, solid carbonic acid, coarse-dispersion powders and hygroscopic particles. Four different methods are commonly used, depending on the synoptic situation: (a) dispersion of stratiform clouds; (b) destruction of convective clouds or reduction of the intensity of shower rains and thunderstorms by seeding; (c) premature initiation of precipitation from clouds on the upwind side of the target area in order to create a "precipitation shadow", i.e. reduction of precipitation over the given site; (d) reduction of rainfall intensity over the target area by intensive seeding of the rain-producing clouds moving toward it, aimed at weakening the mechanism of precipitation formation through "over-seeding", i.e. creating excessive concentrations of ice crystals. However, these studies lack quantitative substantiation that could be verified in a repeatable and consistent manner.

Redistribution of precipitation is a challenging issue to address, due to the current limitations of quantitative precipitation forecasting and especially so for convective rainfall. In the case of the hygroscopic seeding experiments the postulated dynamic effects due to microphysical and dynamical interactions in the cloud and sub-cloud region (WMO, 2000) and with the environment could result in longer-lived or progeny clouds. Another related uncertainty in seeding convective systems is whether a positive effect on some individual clouds (or cloud complexes) will aggregate to result in increased area of surface rainfall.

Debates about the effects of seeding beyond the target area point to the fact that weather modification can be viewed as more than just a means to increase local precipitation. Rather, it can be viewed as a means to alter natural hydrological cycles by increasing the number of times that atmospheric water is recycled at the Earth's surface. As more is learned about the global water balance and as new tools enable the cloud scientist to better understand clouds and their response to seeding, the question of extended area effects likely will become better defined and understood.

Finally but not least, all these effects will have to be considered against the background of climate change and the associated changes in precipitation in time and space globally.

### **3.5 Alternative technologies**

There have been several alternative technologies suggested in the past and we will briefly discuss them in the following paragraphs. It is important to consider that in many cases the scientific basis for these technologies have not been validated in the literature.

#### **3.5.1 Ionization**

The natural electrified state of the atmosphere has been studied for over a century; however, the effect of ionization on the physical properties of aerosols and clouds has rarely been studied in its own right except in thunderstorms (compare Chapter 2).

Numerical modelling shows that ionization/electrical effects can modify the evolution of the droplet size distribution (Khain et al., 2004), and that droplet charging can reduce the time taken for the growth of droplets to raindrop sizes (Harrison et al., 2015). The presence of charges on droplets and aerosol particles can increase collisions among these objects, which would ultimately have effects on precipitation (Tan et al., 2016).

The charges carried by a droplet distribution depend on the local ion concentrations (Harrison and Carslaw, 2003), and can therefore be changed by introducing additional small ions of one or other sign (Clement and Harrison, 1992). Ultimately the effect of charging is to modify the growth parameters of droplets evolving to raindrop sizes.

In the past 20 years a technology has been implemented in several countries based on ionization experiments in Russia (Beare et al., 2010). They claim that by ionization of particles near the surface they could affect clouds. The hypothesis on the chain of processes is as follows:

Initially, negative ions are generated from a corona discharge wire array. The ions become then attached to particles in the atmosphere, which later act as CCN.

These ions are transported to the higher atmosphere by wind, atmospheric convection and turbulence. Through nucleation the electric charges on these particles are transferred to cloud droplets where the electrostatic forces on droplet interaction aid the coalescence of the cloud droplets. This results in enhanced raindrop growth rate and ultimately increasing rainfall downwind.

However, none of the hypothesized chain of events have been validated by either observations or numerical modelling on an area wide scale. The principal action of ions may be significant in a cloud chamber but extrapolating these effects to the atmosphere remains without a scientific basis. Currently, there is no scientific basis that this could increase precipitation.

Further theoretical and experimental studies are needed to understand whether modulation of the aerosol charge around clouds could lead to observable changes in cloud properties. New high spatial resolution atmospheric electrical measurements of both positive and negative ions

combined with aerosol properties and microphysical parameters are needed in order to understand the highly complex and variable aerosol electrical state around clouds. Focused studies of the processes occurring at the level of individual clouds may offer some insight into the mechanisms behind existing cloud-ionization observations.

### **3.5.2 *Electric fields and modification of electricity***

While there is general consensus in the literature (Pruppacher and Klett, 1997) that the electrification of clouds could impact the collision efficiency of large and small ice particles, some other effects have also been postulated.

Stepanenko et al. (2002) found that the concentration of ions in the field of a lightning channel in clouds sharply increases, reaching values of  $10^{11} \text{ cm}^{-3}$ , which exceeds the usual observed concentration by 6 orders of magnitude and more in the cloudy environment. Such a large concentration of ions and sharp gradients in the intensity of the electric fields may modify the microphysical properties of clouds. Experimental studies in a cloud chamber and high-voltage stands in the Main Geophysical Laboratory of Saint-Petersburg (Stepanenko et al., 2002) showed that electric discharges under certain conditions can lead to temperature increase of drops freezing, increase in concentration of crystals and change of their form, to promote ionization of air and to provide a sharp increase in a volume charge of a cloud.

Mikhailovsky (2015) proposed a modification of the electric stage of convective clouds by increasing ice crystal concentrations through seeding for the purpose of strengthening and weakening of the electrification. By regulating the amount of the large and small ice crystals by seeding dispersed into a cloud, it may be possible to induce both strengthening (acceleration) of electrification and its suppression (Galperin et al., 1990; Mikhailovsky et al., 1992).

However, none of these studies have addressed quantitatively how this would impact precipitation at the surface and thus remains in the realm of speculation in terms of rainfall enhancement experiments.

### **3.5.3 *Laser technologies***

Laser-induced condensation has been recently proposed as a possible alternative to more traditional rain enhancement techniques like hygroscopic and crystallizing seeding, due to its potential for triggering condensation in sub-saturated conditions. It is based on the hypothesis that the interaction of the laser filaments with indigenous hygroscopic aerosols could enhance surface-catalysed nucleation processes (heterogeneous nucleation) through the broadband illumination co-generated by the laser pulses (Petit et al., 2011; Leisner et al., 2013). Rohwetter et al. (2010) and Henin et al. (2010) demonstrated that self-guided ionized filaments generated by ultra-short laser pulses are also able to induce water cloud condensation in the free, sub-saturated atmosphere. Laser filaments and their co-generated broad-spectrum light structures can induce photochemical reactions to modify the hygroscopic properties of atmospheric aerosols (Saathoff et al., 2013).

Although condensation has been shown to occur on very local scales by the use of lasers to generate CCN in sub-saturated air, questions remain on the relevance of this technology to precipitation enhancement and, thus, the approach is currently lacking the scientific basis to enhance precipitation in the atmosphere.

### **3.5.4 Acoustic waves**

A hail or acoustic cannon is a shock wave generator. A mixture of acetylene and oxygen is ignited in the lower chamber of the machine. As the resulting blast passes through the neck and into the cone, it develops into a shock wave. This shock wave then travels at the speed of sound through the cloud forming above, a disturbance which manufacturers claim increases collision coalescence growth of tiny water droplets, thus producing bigger raindrops. The cannon is also claimed to disrupt the growth phase of hailstones. Wieringa and Holleman (2006) review the application of cannons to weather modification, and they find no scientific basis for this methodology.

## **3.6 Conclusions and recommendations**

In this chapter current knowledge of the result of seeding agents on the main types of target clouds were presented.

Winter orographic clouds are seeded to convert inherent supercooled liquid water into snow and thus increase the precipitation in water catchments. Probably due to the relatively high constraints on the dynamics of such clouds, the reported results are rather encouraging. The stability of the flow over a mountain (represented by the Froude number) and the geometry of the mountain (represented by its aspect ratio) are determining parameters, as well as the stratification of the deeper atmosphere. Best results seem to occur for silver iodide aircraft seeding of clouds that have already a natural tendency for precipitation formation.

The results for convective clouds are more complex. Those clouds can be seeded through glaciogenic or hygroscopic agents.

In all cases the specific dynamical and thermodynamical environment needs to be taken into account, as well as the ambient background aerosol particle concentration. In particular, a situation can occur when the hygroscopic seeding particles resulting from flares (0.1-1 $\mu$ m) are smaller than the ambient aerosol particles (e.g. sea salt, up to several  $\mu$ m). Such a seeding case can even reduce precipitation. Salt powders may provide larger particles but present operational constraints due to their heavy payload.

- Here, the development of new optimized seeding agents present encouraging alternatives.
- Also, the altitude of seeding is of utmost importance.

An AgI glaciogenic seeding agent (<1 $\mu$ m) injected at cloud base first can act similar to a hygroscopic seeding agent. Due to the size of the particles they will first serve as CCN and participate in the warm rain process. Thus, they might not ascend to the altitudes where they become IN.

Using the concepts of precipitation enhancement to actually reduce rainfall is routinely done in some countries. Generally, seeding clouds with numerous small CCN can reduce the rainfall in the target area, adding credibility to the initial hypotheses.

While generally AgI is used for glaciogenic seeding and flares for hygroscopic seeding, alternative seeding agents are also in use.

- A careful analysis of the local ambient particle population and additional research on the chemical properties as well as size and concentrations of seeding agents to identify optimal conditions are necessary. Constraints on payload and safety also need to be taken into account.

The chapter includes discussion of some alternative approaches to seeding.

One aspect concerns ionization and electrification of the particles and hydrometeors. Even though electrical charges can affect the evolution of a cloud, the exact mechanisms in the natural atmosphere are too poorly known to apply any modification of the charges in a confident way for seeding purposes.

Due to the stress in arid regions, methods are being sought to trigger the formation of clouds out of "thin air". Here, laser technologies have shown promising results in that they can locally modify aerosol particles into small droplets. However, the problem of converting them into precipitation in a dry atmosphere remains unaddressed.

Cannons have been proven to be inefficient in this respect.

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## **4. OBSERVATIONS OF AEROSOL, CLOUDS AND PRECIPITATION**

### **4.1 Introduction**

Recent decades have seen major advances in the technologies for observing clouds, especially through ground-based, aircraft-based and satellite-based remote sensing. Together with advances in numerical modelling (Section 5), technology has played a substantial role in furthering our understanding of the physical processes associated with precipitation enhancement. The measurement of precipitation over a catchment-scale area is more accurate owing to advances in the observation of liquid and solid precipitation from gauges as well as radars and satellites. The synoptic environment in which clouds form can be well represented by local profiling instruments such as radiosondes, multiwave passive radiometers, micro rain radars, wind profilers and lidars and other remote sensing technologies. Scanning radars to delineate cloud dynamics often have both Doppler and dual-polarisation capabilities, as well as being transportable in mountainous terrain. Geostationary satellites now have the spatial, temporal and spectral resolution to provide useful information on both the dynamical and microphysical properties of clouds. There have been major advances in the measurement of aerosol and cloud microphysics from in situ probes and remote sensing technologies.

Thus, current capabilities have significantly improved to allow for observation of cloud processes from the micro-scale to the mesoscale. It is therefore feasible to analyse the detailed evolution of natural clouds and cloud systems, and to identify changes associated with cloud seeding.

### **4.2 Observations of precipitation**

Accurate measurement of natural precipitation and of any artificial enhancement of precipitation is an essential element of the science of weather modification. The spatial and temporal variability of precipitation (especially in convective systems) ensures that accurate measurement remains a challenge. In order to document the sequence of physical processes associated with the initiation and development of precipitation in cloud, it is necessary to have continuous and three-dimensional observations of in-cloud properties. On the other hand, the monitoring of precipitation at the ground over a catchment-scale area is needed to evaluate the practical effectiveness of any precipitation enhancement system.

#### **4.2.1 *Ground-based rain and snow observations***

Ground-based precipitation gauges provide the most accurate means for measuring precipitation at the surface over a catchment-scale area. Villarini et al. (2008) analyse data from 50 rain gauges over an area of 135 km<sup>2</sup> to investigate the uncertainties associated with rainfall estimation on time scales from minutes to a day. It is confirmed that spatial sampling errors are reduced as the temporal integration scale is increased. As the duration of experimental units in cloud seeding projects can currently be a few hours (e.g. Breed et al., 2014; Manton et al., 2011), these uncertainties need to be taken into account when estimating the practical efficacy of cloud seeding. In particular, Villarini et al. (2008) find that to estimate rainfall over an area of 200 km<sup>2</sup> with an uncertainty of less than 20 %, at least 15 gauges are needed for 3-hourly averages, with this number falling to 4 for daily averages.

When precipitation falls as snow, as expected for winter orographic cloud seeding, the uncertainties in measuring precipitation at the surface are greatly enhanced. Weighing gauges and optical sensors are used for snowfall measurement (Gultepe et al., 2016). Rasmussen et al. (2012) summarize the current state of knowledge in the observation of snow, which is often accompanied by strong winds and turbulence. Building on the earlier work of WMO on the intercomparison of measurement techniques (Goodison et al., 1998), they document the sources of uncertainty and identify the most accurate techniques for measuring snowfall. However, they recognize that the benchmark Double Fence Intercomparison Reference (DFIR) wind shield (involving a 12-m and a 4-m fence around each gauge) may not be practical for remote sites, and so an understanding of the uncertainties of sub-optimal but practical measurement approaches is essential. In order to assess the consistency of the wide range of gauges being used by national meteorological services, the WMO Commission for Instruments and Methods of Observations (CIMO) initiated the Solid Precipitation Intercomparison Experiment (SPICE) in 2012 (for example, Buisan et al., 2017). Using some of the gauges at the SPICE site in the Snowy Mountains of south eastern Australia, Chubb et al. (2015) investigate the wind-induced losses from different types of gauges compared with a gauge within a DFIR. For 6-hourly average precipitation, they find that losses of up to 52 % can occur at unfenced gauges, but such losses can be minimised when gauges are located at sites where there is some natural protection from wind.

Martinaitis et al. (2015) suggest that, while gauges are seen as the most accurate means of measuring precipitation, the uncertainties associated with the operation of individual gauges mean that an optimal real-time analysis of solid precipitation should involve a combination of observing systems, to provide quality control of each gauge. An important component of the quality control on precipitation gauges in the field is regular maintenance and calibration.

#### **4.2.2 Ground-based radar observations**

While in situ gauges provide the most accurate means of measuring precipitation at the ground, it is not always feasible to provide a dense network of gauges. Difficulties arise where the orography is steep and rough, or when the precipitation is more heterogeneous as in small-scale convective storms. These difficulties may be overcome through the use of scanning radars. Much research has been carried out on the application of radar to the estimation of precipitation over catchment-scale areas, while recognizing that there are significant uncertainties in relating radar reflectivity to rainfall rate (for example, Campos and Zawadzki, 2000). Rosenfeld et al. (1994) used a probability matching technique to demonstrate that such uncertainties can be reduced by careful calibration with rain gauges (such as establishment of Z-R relationships, removing ground clutters, attenuation corrections, etc.), and these types of approaches continue to be developed (e.g., Hasan et al., 2016).

A major technological advance in recent decades has been the application of dual-polarisation radar to rainfall estimation (Brandes et al., 2002), where information on hydrometeor shape and phase can be utilised when calibrating radars with in situ disdrometers. With the ready availability of real-time computing power and increasing research on the relationship between particle size distribution and hydrometeor type, the algorithms for precipitation estimation from dual-polarisation radars continue to be improved (for example, Cifelli et al., 2011). A

network of disdrometers and micro rain radars at strategic locations around the radar observation area can be used for calibration and validation of surface rainfall data. Ground based radars are used for cloud seeding decision-making as well as for assessing the efficacy of seeding.

National-scale systems often include dual-polarisation radars to provide high spatial and temporal resolution estimates of precipitation (for example, Bringi et al., 2011). Krajewski et al. (2010) compare radar-based estimates of rainfall with those from rain gauges, following the methodology of Wilson and Brandes (1979). They showed that advances in hardware and software systems have led to significant improvements over the last 40 years, with the mean difference between radar estimates and rain gauges being about 42 %, but that difference is reduced to about 21 % when the systematic (multiplicative) bias is removed.

Large-scale radar systems continue to evolve to include multi-radar multi-sensor technologies, combining radar measurements with data from gauges, satellites and numerical weather prediction models (Zhang et al., 2016). In regions where these systems provide accurate and reliable precipitation estimates on space scales of about a kilometre and time scales of at least an hour, they serve as a valuable resource for reliable data on the basic variables for precipitation enhancement projects.

An emerging technique for monitoring the spatial and temporal variability of precipitation is through measurement of the attenuation of microwave radiation associated with commercial cellular telephone networks (for example, Messer et al., 2006). Overeem et al. (2016) demonstrate that the technique can be used to effectively monitor precipitation over an area of  $3.5 \times 10^4 \text{ km}^2$ , but frozen or melting precipitation can lead to uncertainties. The precision of the technique is also reduced in rural areas where the network coverage is low. Nonetheless, Haese et al. (2017) show that combining the data from cellular networks and rain gauges may provide an improved estimate of precipitation over a large area.

The computation of precipitation and related cloud properties from radar is complex, requiring careful management and development of both hardware and software. Calibration is an essential routine activity, with Louf et al. (2018) noting the regional variability of radar parameters and the need for an integrated approach to calibration of both basic and dual-polarisation radars. Saltikoff et al. (2017) document the challenges in maintaining a weather radar network and encourage further discussion within the international radar community to promote best-practice in the operation and monitoring of radars. Many research groups have developed software to generate physically-related variables from raw radar data. While new concepts are shared through scientific publications, the international radar community is now collaborating in the development of open-source software, leading to readily-accessible analysis tools with known progeny (Heistermann et al., 2015).

#### **4.2.3      *Space-borne observations***

Satellite-based estimates of precipitation have also evolved considerably over the last decade. Since the routine availability of meteorological geostationary satellites in 1979, the Global Precipitation Climatology Project (GPCP) has provided large-scale (250 km) monthly estimates of precipitation across the globe (Xie and Arkin, 1997). While a useful product for climatological studies, GPCP is generally too coarse in space and time for weather modification

applications. However, the launch of the Tropical Rainfall Measuring Mission (TRMM) in 1997 (Simpson et al., 1996) introduced a satellite-based rain radar, which yielded high spatial-resolution information on precipitation over the tropics and subtropics for nearly twenty years. These data were valuable in delineating small-scale features of precipitating systems, but the return-period was too large for most weather modification research. The more recent Global Precipitation Measurement (GPM) mission uses a combination of active and passive instruments on a number of satellites to provide precipitation estimates at a temporal resolution of a few hours (Skofronick-Jackson et al., 2017). The combined multi-sensor, multi-frequency measurements reduce uncertainties and can give important data on light rain as well as frozen precipitation. These data, while useful as stand-alone products, feed into national and regional quantitative precipitation estimates combining data from a range of instruments and models at high spatial and temporal resolution. Integrated methods, involving several instruments are used in recent years for precipitation research; for example, Iguchi et al. (2012) use 94-GHz radar, lidar and CloudSat radar with high-resolution numerical simulations. Sun et al. (2018) provide a review of global precipitation data sets based on both gauges, which tend to yield daily or even monthly values, and satellites, which can give estimates on time scales from hours to a month but which suffer from a number of limitations, especially over complex terrain.

### **4.3 Observation of the synoptic environment**

Although precipitation enhancement is invariably associated with microphysical changes in cloud, the character and development of any cloud is also controlled by larger scale processes. It is therefore essential to observe the synoptic environment of the clouds in any precipitation enhancement project. Indeed the synoptic environment is generally one of the key parameters in determining when clouds are suitable for seeding, and it is usual to install dedicated sounding sites during projects with releases every few hours during periods of potential seeding (Manton et al., 2011; Breed et al., 2014).

The passive remote sensing devices such as microwave passive radiometer profilers if properly calibrated are able to give detailed vertical profiles of temperature and humidity along with liquid water profiles up to 1.5 and 10 km from the ground, including information on supercooled liquid water (Ware et al., 2013; Sanchez et al., 2013; Balaji et al., 2017). A W-band radar with an integrated radiometer profiler at 95GHz for LWC and IWC profiles with Doppler and polarized capability is useful in understanding precipitation type and cloud system dynamics (Gultepe et al., 2017). Wind profilers are also used to get information on the vertical variation of winds, which may be crucial to identify the shear layers and other inhomogeneities in the atmosphere. Information on the diurnal cycle of the thermodynamics and dynamics can provide details to identify the time and region of cloud development; it is also relevant to cloud seeding decision-making.

When analysing cloud data, it is necessary to have a broader representation of the synoptic environment than that provided by local soundings. This representation is best given by analyses from numerical weather prediction systems. When seeking analyses that are dynamically consistent over an extended period of time, it is appropriate to utilise reanalysis products (for example, Dee et al., 2011). Geostationary satellite imagery also provides a very useful representation of the synoptic environment involving cloud systems. These satellites now yield multi-spectral imagery on time scales of order 10 minutes and space scales of 1 or 2

km (Bessho et al., 2016; Schmit et al., 2017). Such information, together with high-resolution weather forecasts, can be used to support weather briefings, and so it is an integral component of any cloud seeding programme.

#### **4.4 Observations of cloud dynamics**

For some decades the most effective means of studying the dynamics of clouds and cloud systems has been through scanning radars. Software systems, such as Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN – Dixon and Wiener, 1993) and ASU-MRL (Abshaev et al., 2010), have provided detailed information on the initiation and development of cumulus cloud cells, based on radar reflectivity alone. Technological developments, such as Doppler and dual-polarisation capabilities as well as increased portability, have led to major advances in the observation of the dynamics of all cloud types. Integration of radar, satellite, lightning and radio-sounding data on one map by ASU-MRL software system (Abshaev, 2010; Dimitrovski et al., 2016) provides helpful information for cloud seeding, storm warnings, flash flood forecasts and hydrological assessments (Abshaev, 2010; Sinkevich et al., 2016 and 2017).

Pokharel et al. (2014) demonstrate that a combination of aircraft-based and ground-based radars can identify changes in cloud structure associated with cloud seeding. An aircraft-based W-band (3 mm) Doppler radar (Wang et al., 2012) can delineate detailed cloud structure by scanning either above or below the aircraft. An X-band (3 cm) Doppler-on-Wheels radar can be readily transported to particular sites to provide full-volume scans, as well as vertical transects aligned with the prevailing wind. Even more portable are (K-band; 1.2 cm) Micro Rain Radars, which provide vertical profiles of precipitation (Maahn and Kollias, 2012) and can be deployed in mountainous terrain. The combination of such radar systems yields comprehensive information on the spatial and temporal evolution of cloud systems in seeded and unseeded conditions.

Radar technology for meteorological applications continues to evolve with imaging radars (using generalized phased array methods) yielding rapid-update three-dimensional scanning of cloud systems (Isom et al., 2013). Kurdzo et al. (2017) compare the capabilities of the available rapid-scanning X-band radar technologies showing volume scan times on the order of 10 s can be achieved. The development of such technology means that the continuous observation of the dynamics and structure of cloud systems is essentially feasible.

A new S-band aviation radar tracking system with phased-array antenna and Doppler capability is currently being developed (Abshaev et al., 2015) with a scanning period of 10 s. It provides better understanding of the most complex and fast developing convective processes. The radar has been installed at several sites in the Northern Caucasus, where it has been used to measure hail and heavy rain in complex terrain.

The range of current technologies available to observe cloud dynamics can be used to optimize decision-making on the time and location for seeding mixed-phase clouds, by identifying the movement of convective clusters and precipitating cloud-bands. Thus the technologies are valuable both for initial decision-making and for analysis of the impacts of seeding. The most recent generation of geostationary satellites (Bessho et al., 2016; Schmit et al., 2017) also provides new opportunities for monitoring cloud structures on space scales of about

1 km and time scales of about 10 minutes over very broad regions. Thus satellites are able to complement ground-based radar in observing the structure and dynamics of cloud systems.

As noted above, ground-based and satellite-based observations are usefully supplemented by aircraft observations of the dynamics and structure of clouds. Using a vertical-plane dual-Doppler radar, Geerts et al. (2015) take direct measurements of the vertical hydrometeor motion. They were able to analyse the growth and transport of snow over a mountainous region and to identify different types of conditions associated with orographic precipitation.

## **4.5 Aerosol and cloud microphysics measurements**

### **4.5.1 Microphysics**

Precipitation enhancement always involves the inducement of a change in the microphysical properties of cloud, and so it is essential to have comprehensive and systematic measurements of the chain of cloud processes extending from aerosol, cloud and ice nuclei to precipitation at the ground. Aircraft provide the means of collecting a full range of microphysical measurements both in cloud and in the cloud environment. Geerts et al. (2010) show how aircraft-based W-band Doppler radar and cloud lidar can be used to identify changes in the microphysical properties of winter orographic cloud due to seeding with silver iodide. In particular, they find that such changes are well displayed through the use of contoured frequency by altitude diagrams (CFADs), which were introduced by Yuter and Houze (1995). Recently French et al. (2018) employ a comprehensive network of instruments to observe the microphysical and dynamical development of orographic cloud following seeding with silver iodide.

While aircraft are essential in the collection of in situ data on the microphysics of clouds, valuable measurements can also be obtained from ground-based instruments. Delanoë et al. (2016) describe a low-power 3-mm Doppler cloud radar that can be adapted to study the microphysics of a range of cloud types. Both on aircraft and on the ground, it is common to operate a cloud lidar in conjunction with a cloud radar (for example, Wang et al., 2009). Lidar is particularly effective in determining the phase of cloud particles, as well as cloud top or base. Aerosol loadings can also be detected from lidar.

The additional information provided by dual-polarisation radars leads to data on the phase and shape of hydrometeors, which can be calibrated against disdrometers (for example, Thurai et al., 2009). Video disdrometers (Brandes et al., 2007) provide detailed information on the nature of precipitation-size particles, and so they can be used to verify the seeding hypothesis and the efficacy of seeding. A range of optical techniques is used to identify and count smaller cloud particles. For example, Baumgardner et al. (2014) describe an instrument that uses scattered light to distinguish ice from liquid water particles in the size range from 2 to 50  $\mu\text{m}$ . Such instruments are commonly flown on aircraft to measure cloud particles from a few to thousands of micrometres.

The accurate measurement of cloud particles is complicated by the large range of their sizes, shapes and concentrations, as well as the high spatial and temporal variability of cloud microphysics and dynamics. Cloud particles can range from spherical water droplets to complex dendritic ice crystals. Water drops and ice can coexist and their concentrations are

highly variable. Cloud droplet, ice particle and raindrop distributions extending in size from 2 to 10,000  $\mu\text{m}$  are measured in situ by forward-scattering probes and particle-imaging probes. Drizzle formation needs to be studied with probes that can give accurate measurements of large particles (Baumgardner et al., 2017). A range of airborne probes is therefore needed to properly support a cloud seeding programme.

A particular measurement challenge arises with the sampling of particles in mixed-phase convective cloud, where large particles that play an important role in the development of precipitation occur at very low concentrations. Observation of these hydrometeors requires sampling of the extreme tails of the distributions, but the inherent spatial and temporal variability of cloud particles means that large sampling errors are likely (Baumgardner et al., 2017).

The measurement of ice particles is further complicated by the potential for shattering as they impact on the instrumentation, leading to biases in the estimates of small particles. Baumgardner et al. (2017) summarize the current techniques for in situ measurement of ice particles. As with radar data, many groups around the world are developing software to analyse the raw data from particle probes. McFarquhar et al. (2017) describe a series of international workshops at which such groups aim to ensure the consistency and accuracy of the various analysis systems for particle probes.

#### **4.5.2 Supercooled liquid water (SLW)**

Most strategies for precipitation enhancement involve the transformation of supercooled liquid water (SLW) to ice, and detailed measurement of SLW is essential for both research and operational activities. Microwave radiometry (Huggins, 1995; Osburn et al., 2016) provides an effective means of measuring profiles of liquid water from the ground, but care is needed in conditions where rain may affect the radiometer radome (Araki et al., 2015). Hogan et al. (2005) use a dual-wavelength microwave radar to estimate liquid water profiles in stratiform cloud. Illingworth et al. (2007) describe the use of active and passive ground-based remote-sensing instruments to evaluate the representation of clouds in operational NWP models. Such instrumentation provides detailed profiles of SLW, and so it can be used to determine the suitability of clouds for seeding.

Direct measurement of liquid and ice water from aircraft is discussed by Baumgardner et al. (2017) generally using hot-wire sensors. The liquid and ice water content can also be estimated by integration of the particle distributions, found from particle counters.

#### **4.5.3 Satellite observations**

Since the launch of polar-orbiting satellites with the Advanced Very High Resolution Radiometer (AVHRR), it has been possible to carry out climatological and case studies of cloud properties across much of the world. Kuji et al. (2000) show how effective particle size and liquid water path can be derived from AVHRR data, and Rosenfeld (2000) uses AVHRR data to study the impacts of urban pollution on cloud properties. Since about 2000, the Terra and Aqua satellites have carried the Moderate-Resolution Imaging Spectro-radiometer (MODIS), which is able to provide estimates of a range of cloud optical and microphysical variables, including effective particle size, liquid water path and ice water path (Platnick et al., 2017).

These data have been used to compare the frequency of occurrence of winter SLW in different regions as a measure of regional suitability for cloud seeding (Morrison et al., 2013).

The MODIS observations are part of the contribution of the A-Train constellation of satellites, which aim to yield data on a range of cloud and aerosol properties. Another contribution is from CloudSat (Stephens et al., 2002), which carries a cloud radar yielding liquid and ice water content profiles in clouds. Although the spatial and temporal coverage of these satellites is limited, they can provide high spatial-resolution information on clouds for both case and climatological studies.

A new era of cloud microphysical data from satellites has started with the launch of geostationary satellites with 10-minute hemispheric imagery with spatial resolution of about 1 km. These satellites (Schmit et al., 2017; Iwabuchi et al., 2018) provide data in 16 spectral bands, so that they can provide information on cloud phase and particle size as well as basic data on cloud top height and temperature.

#### **4.5.4      *Aerosol particles***

Aerosol particles influence many cloud properties, such as cloud droplet number and size (McComiskey et al., 2009; Shao and Liu, 2009), cloud cover and lifetime (Kaufman and Koren, 2006; Small et al., 2009), as well as precipitation initiation (Rosenfeld et al., 2008; Khain, 2009; Sorooshian et al., 2009). A combined approach using the optical and electrical mobility properties of aerosols can be used to monitor the aerosol size distribution. The complete aerosol size distribution including that of submicron particles throughout the lower and middle troposphere needs to be measured in both the ambient and seeded areas.

Sakai et al. (2013) compare the aerosol optical properties from a dual-wavelength polarization lidar with the microphysical properties from aircraft-based instruments. Their results show the utility of lidar for the characterization of aerosols, but small CCN can sometimes be difficult to detect by lidar.

Due to the potential influence of aerosol particles on climate, there are a number of international projects aimed at quantifying the distribution of aerosols, including CCN. For example, Schmale et al. (2018) describe a comprehensive data set from 11 sites across the northern hemisphere on naturally occurring aerosol particles and CCN. While such studies provide useful climatological data, precipitation enhancement activities need in situ measurements of CCN, which are usually obtained from aircraft-based counters (for example, Wang et al., 2012).

#### **4.5.5      *Ice nucleating particles (INP)***

Heterogeneous nucleation of ice particles occurs due to the presence of ice nucleating particles (INP) that are present in the atmosphere, eventually influencing surface precipitation through complex processes (Kanji et al., 2017). INP concentrations, however, are seldom observed, and there are only a few instruments capable of analysing them. There is a substantial lack of knowledge of the key properties of INP, including their concentration, composition and ice-nucleating capability. Indeed, there remains uncertainty on the specific properties that make a particle an INP.

The measurement of INP presents a number of challenges, especially owing to the process of ice multiplication in clouds. However, continuous flow diffusion chambers can yield consistent measurements, and other techniques are being developed (Cziczo et al., 2017; Garimella et al., 2017). Nonetheless, the character of natural INP remains an important climate variable that is not being observed systematically around the world. DeMott and Prenni (2010) discuss the need for documenting biological sources of aerosols acting as ice nucleating particles. Some of the recent measurements (Twohy et al., 2010) indicate the potential role of biomass-burning aerosol particles in ice formation in regions with relatively low concentrations of other INP. This result is consistent with the finding of Ardon-Dryer and Levin (2014) that aerosols from low-temperature biomass burning are not particularly effective as INP.

#### **4.5.6 *Snow chemistry and physics***

Observations of trace chemicals in snow can also be used to understand the nature of background aerosols and also to measure the effectiveness of cloud seeding. Warburton et al. (1995) measured the concentration of silver in snow in both seeded and unseeded conditions to confirm the accurate targeting silver iodide released from ground-based generators. They also used the technique of Chai et al. (1993) to measure the ratio of silver to a passive tracer (indium) to demonstrate that seeding has increased the concentration of ice nuclei above the natural level.

There is also interest in measurement of the physical properties of snow on the ground, investigating potential changes in habit and density associated with cloud seeding. For example, Holroyd et al. (1995) use a particle imaging probe to identify changes in ice particle concentration and habit due to silver iodide seeding in Utah.

#### **4.5.7 *Emerging technology***

Recently, some emerging technologies have been suggested as potential techniques for cloud microphysical observations. For example, Axisa and DeFelice (2016) discuss the operational efficiency and evaluation accuracy that could be obtained through the use of unmanned aerial vehicles (UAVs) and related instrumentation, especially for convective mixed-phase clouds. UAVs could facilitate real-time monitoring of cloud fields as well as the targeting of clouds, based on physical measurements of basic parameters such as updraft, liquid water content, cloud depth and cloud base height.

### **4.6 *Laboratory measurements***

Chapter 4 is focused on the observation of properties of clouds and cloud systems in the atmosphere related to precipitation enhancement science. However, while precipitation enhancement is clearly a field activity, there are significant observations taken in laboratories that are relevant. When reviewing the challenges associated with the production of ice in tropospheric clouds, Cantrell and Heymsfield (2005) note the value of cloud chambers in developing our understanding of ice nucleation and multiplication. Cloud chambers continue to be installed in laboratories around the world. Chang et al. (2016) summarize the historical application of cloud chambers, while introducing a chamber in which the effects of turbulent

mixing on cloud microphysics are studied. These facilities provide infrastructure to elucidate some of the outstanding aspects of cloud microphysics, such as the transition from condensation to collision-coalescence as the dominant process for droplet growth.

Cloud chambers are especially useful for studies of the effectiveness of CCN and INP. Drofa et al. (2010) use a cloud chamber to demonstrate how the introduction of large salt particles can lead to a droplet distribution that includes large drops. Tajiri et al. (2013) describe a cloud chamber to simulate adiabatic parcel conditions associated with cloud formation in the atmosphere, and Tajiri et al. (2015) assess the CCN and INP potential of a range of materials used for either hygroscopic or glaciogenic seeding.

Clean laboratories are an essential component of any snow chemistry measurements taken during a precipitation enhancement project. Because the data relate to trace chemicals, it is important to avoid all potential sources of contamination. Similarly, laboratory studies are essential to support the development of potential cloud seeding materials and in the calibration of the technologies used to disperse such materials. A precise knowledge of the size and number concentrations of seeding particles, as well as their chemical composition, is essential in order to assess their interaction with the ambient aerosol population.

#### **4.7 Conclusions**

In recent decades, instrument development for probing and understanding clouds has made considerable progress. Different aspects of the clouds need to be followed to characterize the natural as well as the seeded cloud.

The essential indicator of success of a precipitation enhancement project is the observation of increased precipitation on the ground above the naturally expected level. The natural variability of precipitation means that the detection of increased precipitation is a major challenge. This challenge is especially difficult for convective cloud systems, where both spatial and temporal variability are high, leading to substantial "noise" that can mask a relatively small "signal" of increased precipitation due to seeding.

A network of precipitation gauges is usually employed to provide consistent measurements of surface precipitation. However, these measurements can have significant uncertainties when precipitation falls as snow, which is common for wintertime orographic cloud systems. Increasingly, both basic and dual-polarisation radars are used to complement rain gauges and to provide high spatial and temporal coverage. It is essential that radars are routinely calibrated to account for local environmental conditions. Disdrometers play an important role in radar calibration.

Analysing radar and other remote sensing data from cloud systems is a complex process. Software systems are being developed to support this analysis, by characterising and tracking individual storm cells within the overall synoptic environment.

The range of remote-sensing instruments is increasing to include micro rain radars, cellular telephone networks, rapid-scan phased-array radars and mobile Doppler radars. All these approaches supplement the rain gauge observations, as well as providing some additional information on the nature of the precipitation and its variability. Aircraft-based radars and

lidars provide details on the spatial and temporal development of precipitation in both the natural environment and when seeding takes place. The new generation of geostationary satellites, with high spatial, temporal and spectral resolution, opens opportunities for consistent monitoring of cloud-top microphysical characteristics.

Detailed in situ microphysical and aerosol properties are observed through a range of particle probes. Observations of the vertical variation of ambient aerosol size distributions are very important. Sampling the size distribution of seeded aerosol particles can also give key understanding on their impact on clouds. Sampling in mixed-phase convective cloud has a substantial challenge because there is increasing evidence that large but low concentration droplets, associated with giant CCN, have an important role in the development of precipitation in these clouds. Detailed quality control for mixed phase hydrometeor measurements should be part of the scientific investigation. Moreover, given the dearth of knowledge of the physics and chemistry of INP, both climatological and several case-study observations of INP are needed to support the fundamental aspects of precipitation enhancement science.

Laboratory studies can assist in increasing knowledge of natural INP, and in the development and characterisation of artificial INP for cloud seeding. Details of the microphysics in clouds and of the interactions between microphysics and dynamical mixing can be simulated in cloud chambers; in particular, the transition of droplet growth from condensation to collision-coalescence should be further studied.

The technology to observe cloud properties continues to expand, and these technologies involve complex hardware and software that need to be routinely calibrated and maintained. There is increasing international collaboration amongst research groups to develop and share systematic approaches to these tasks, moving towards recognized international best practice.

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## **5. MODELLING OF NATURAL CLOUDS AND SEEDED CLOUDS**

### **5.1 Introduction**

It is well known that a large number of samples are required in order to evaluate seeding effects on surface precipitation using statistical methods due to the large variability of natural precipitation (Dennis, 1980). Along with recent advances in computer technology and performance of numerical models, quantitative evaluation of seeding effects using numerical models is gradually becoming realistic and effective. Numerical models are also becoming an indispensable tool for developing various technologies related to precipitation enhancement such as assessment of seedability, and development of an optimum seeding method and an efficient statistical evaluation method with physical predictors of precipitation in target area.

In this chapter, we review recent research trends using numerical models in precipitation enhancement field mainly after Orville's (1996) review paper on cloud modelling in weather modification and the report entitled "Critical issues in weather modification research" by the National Research Council (2003) were published.

### **5.2 Numerical models used in weather modification**

#### **5.2.1 *Types of model frameworks***

In the field of cloud physics and weather modification research, numerous numerical models of various types have been used for many years. The models are classified as zero, one, two and three-dimensional, and time-dependent or steady-state. The models are also classified from the viewpoint of the coupling between cloud microphysics and dynamics. The uncoupled kinematic models, where the dependent variables such as the airflow are prescribed, in the past treated the microphysics in more detail as compared with the coupled models (Orville, 1996), but the rapid advances in computer capacities result in a full coupling in most recent studies.

As was summarized in Flossmann and Wobrock (2010), the geometry of the supersaturation fields of a parcel model dynamics and the 1.5D model are generally not very realistic as they are too homogeneous. This concern is overcome in 2D and 3D models, where large parts of the visible cloud can be subsaturated and up and downdrafts exist at all altitudes side by side. Furthermore, the maximum supersaturation values in the simple dynamic frameworks are generally too high. As also pointed out by Stevens et al. (1998) the lack of a correct energy cascade in 2D distorts the complex cloud structure and consequently only complete 3D simulations can reproduce actual field results (e.g. Leroy et al., 2009; Planche et al., 2010). Only 3D simulations confirm the existence of large sub-saturated regions in clouds, a permanent nucleation and deactivation process of hydrometeors and highlight the dependence of the most probable supersaturation on the initial aerosol particle population (Planche et al., 2010).

Simplified dynamics can be conveniently used for sensitivity or process studies; however, they cannot yield quantitatively accurate results.

Numerical experiments on cloud seeding using one, two or three-dimensional, time-dependent models began in the late 1950s, the mid-1970s and the mid-1980s, respectively. Complete 3D model simulations using nested domains, large-scale forcing and a sophisticated microphysics scheme have only become available in the last decade (see Hashimoto et al. 2008), due to the advances in computer technology. However, only these can be expected to yield reliable seeding results, while all earlier, simpler approaches are listed here for the sake of completeness. The earlier models can be used to derive sensitivities but generally they tend to over-predict seeding impacts due to their simplified dynamics.

Zero-dimensional models, which are often called parcel or box model and are Lagrangian in nature, can most accurately express cloud particle generation processes from aerosol particles (activation of aerosol particles as CCN and INP and subsequent diffusional growth). Due to the characteristics (zero-dimensional) of the parcel model, it is not suitable to represent the interaction with other hydrometeors during the falling of the precipitation particle, but is suitable for simulating the particle growth up to the early stage of precipitation particle formation. In recent research on precipitation enhancement, parcel models have been mainly used for evaluating the effect of hygroscopic seeding.

Steady-state models, which are also called kinematic models, are a framework that provides the airflow structure inside and outside the cloud. They were originally developed for comparison of cloud microphysical parameterizations employed in a number of cloud-resolving models and numerical weather prediction models. One-dimensional and two-dimensional kinematic models are often used, e.g. one-dimension kinematic driver model (KiD, Shipway and Hill, 2012) and two-dimensional kinematic model for testing warm clouds (Szumowski et al., 1998). The time change of the airflow structure is pre-described and the influence on the airflow field due to the latent heat release and the loading of hydrometeors through the cloud microphysical processes are not taken into consideration. Thus, these models are often called "uncoupled" kinematic model. The models incorporate a detailed bin spectral cloud microphysics scheme including aerosol particles as well as a bulk cloud microphysics scheme. In particular, since the change in particle size distribution due to activation of CCN and subsequent diffusion growth can be calculated more accurately than the bulk schemes incorporated in ordinary non-hydrostatic models (NHMs), they are used to evaluate the effect of hygroscopic seeding on surface rainfall (Kuba and Murakami, 2010).

In the past, numerical seeding experiments for a single cloud were carried out by incorporating the bulk or bin spectral cloud microphysical parameterizations into axisymmetric non-hydrostatic models or two-dimensional non-hydrostatic models. However, recently, cloud seeding simulations have also been performed for multiple clouds, namely a cloud system, using regional three-dimensional NHMs, often with nested domains. By taking the terrain into consideration and taking the forecast result of parent models or objective analysis data as the initial and boundary conditions, realistic simulations have become possible.

For cloud microphysical parameterizations, the bulk scheme or bin spectral scheme is adopted, and in some models aerosol particles acting as CCN and/or INP are explicitly handled. However, since the spatial resolution of the models is 1 km or several hundreds of metres, which is too coarse compared to the initial spatial extent (10 m) of seeding materials, advection/diffusion of seeding materials tends to be overestimated. In order to overcome such weaknesses of NHMs, large eddy simulation (LES) models have become popular recently.

LES models have a spatial resolution of several tens of meters and a three dimensionally isotropic grid system, and can resolve the turbulence structure at a small scale. Besides the bulk microphysical parameterization, there are models that incorporate the bin microphysical parameterization, and parameterizations including the prognostic variable for aerosols acting as CCN and/or INP. But the models gradually become complex, requiring large memory and computation time.

Although three-dimensional time-dependent models with a coupling between microphysics and dynamics (three-dimensional NHMs) are getting more and more popular these days, various kinds of numerical models (two-dimensional non-hydrostatic models, kinematic models, parcel models and others) are still used for various aspects of precipitation enhancement research.

### **5.2.2 Cloud microphysics**

From the viewpoint of precipitation enhancement research, the deployed cloud microphysical parameterization is important as it greatly affects the accuracy of numerical seeding experiments. There are various cloud microphysical parameterizations coupled to non-hydrostatic models currently in use. For example, in the bulk cloud microphysical parameterization, hydrometeors are categorized into cloud water (cloud droplet), rain, cloud ice (ice crystals), snow, and for some models, hail, and their particle size distributions are assumed by an inverse exponential function or a gamma function and the change in the total mass (single-moment bulk scheme) or in the total mass and number (double-moment bulk scheme) of the particles in each category is predicted. Triple-moment bulk schemes, where 2<sup>nd</sup> or 6<sup>th</sup> moment of particle size in addition to 0<sup>th</sup> and 3<sup>rd</sup> moments of particle size is predicted, are used in order to represent the shape parameter of a gamma distribution in some studies (Milbrandt and Yau, 2005; Loftus and Cotton, 2014; Chen and Tsai, 2016; Lompar et al., 2016). In the bin spectral microphysical parameterizations, the particle size range of each particle category is divided into particle size categories of several tens of particles, and the change in particle number (single-moment bin scheme) or in particle mass and number (double-moment bin scheme) within each size category is calculated, and the change in particle size distribution is simulated in detail. Currently, also bin microphysics models exist that includes a bin resolved representation of aerosol particles (Khain et al., 1999; Yin et al., 2000a; Flossmann and Wobrock, 2010). Such a model allows explicit consideration of the nucleation of drops and ice particles on the ambient aerosol population and simulates different clouds in different pollution conditions (Leroy et al., 2009; Planche et al., 2010). Recently, also the nucleation of ice particle along different INP modes have been taken into account (Hiron and Flossmann, 2015).

A cloud microphysical parameterization was developed to more accurately handle the conversion from cloud water to rain (raindrop formation process) by adding a category of drizzle in between cloud water and rain (Saleeby and Cotton, 2004). This type of microphysical parameterization may be also useful in simulating the formation of raindrop embryos directly from giant and ultra-giant hygroscopic particles contained in hygroscopic seeding material. Also, instead of classifying precipitation particles into rain consisting of liquid water and snow/graupel/hail consisting of solid water (ice), a parameterization was developed to predict the separate behaviour of the liquid water component and the solid water component of precipitation (Ferrier, 1994).

Recently also a new bulk microphysics scheme has been developed that predicts various ice particle properties for a single ice-phase hydrometeor category through the use of four appropriate prognostic ice variables: total mass, rime mass, rime volume, and number (Morrison and Milbrandt, 2015).

There has been great progress in the development of schemes to represent microphysical processes in numerical atmospheric models. However, there remain some significant challenges in reducing the uncertainties associated with microphysics in models. Jensen and Nugent (2017) note that particle growth near cloud base, where condensation dominates but coalescence is commencing, is difficult to capture in a complex 3-D model. There is even a challenge for bin-microphysics schemes, where the interactions among bin groups become very substantial. Perhaps most disturbing is the number of studies that are suggesting that the choice of microphysics scheme in a model affects both cloud morphology and the distribution of precipitation. For example, White et al. (2017) show that the differences in cloud properties due to changes in the microphysics scheme are larger than those due to perturbations in the cloud droplet concentration near cloud base associated with aerosol differences. While this result is expected, taking into account that bulk parameterizations assume a size distribution instead of calculating it, it also highlights the need for more research to identify the most reliable microphysics parameterizations.

### **5.2.3 Seeding schemes**

Seeding schemes used in numerical models are categorized as first-, second-, and third-generation seeding schemes. This terminology refers to the way in which cloud seeding is simulated in the models. The first-, second-, and third-generation seeding schemes refer to the practices of changing supercooled cloud liquid to ice at some arbitrarily predetermined temperature, creating more ice by arbitrarily adding ice crystals to the domain, and simulating a seeding agent field and allowing the seeding agent to interact with the cloud and precipitation field, respectively (Orville, 1996).

In precipitation enhancement research, apart from cooling agents like dry ice etc., by introducing artificial INP and artificial CCN as cloud seeding materials into clouds and changing cloud microstructures, the augmentation of precipitation amount is determined through modulations of precipitation processes. Therefore the treatment of aerosol particles as CCN and INP in numerical models becomes very important.

Models with prognostic variables for aerosol particles acting as CCN had been developed starting in the 1980s in the study of the aerosol indirect effect (Warner, 1973; Takeda and Kuba, 1982; Johnson, 1982; Flossmann et al., 1985) and such aerosol schemes were applied to 2D non-hydrostatic models from the beginning of 2000 in the field of precipitation enhancement research (Yin et al., 2000a). The history of numerical models dealing with aerosol effects on clouds and precipitation is also reviewed in detail by Feingold et al. (2009).

On the other hand, models with aerosol particles acting as INP (AgI), as prognostic variables, were used in cloud seeding studies since the 1980s.

Regarding dry ice seeding, the simple way to evaluate its seeding effect is to introduce a vertical seeding curtain consisting of ice crystals whose concentrations are calculated based on an assumed seeding rate of dry ice pellets and aircraft flight speed. In the late 1990s, some models had a prognostic variable for the mass concentration of dry ice pellets, calculated their sublimation rate in the atmosphere assuming the size of dry ice pellets, and calculated the production rate of the number of cloud ice, assuming that  $10^{13}$  particles of cloud ice are generated while 1g of dry ice pellets sublime in clouds during their fall. The production rate of ice crystals due to the sublimation of dry ice pellets in clouds is based on Fukuta et al. (1971) experimental result.

Aircraft seeding of dry ice pellets is realistically simulated, e.g. the delivery of dry ice pellets from aircraft flying in a figure-eight pattern or other patterns (Hashimoto and Murakami, 2016).

There are numerical simulations dealing with liquid CO<sub>2</sub> seeding from aircraft (Guo et al., 2006; Seto et al., 2011). In their seeding scheme, rather than directly treating the mass of liquid CO<sub>2</sub> as a prognostic variable, the mass of liquid CO<sub>2</sub> delivered to the grid box is calculated based on the seeding rate of liquid CO<sub>2</sub> and flight course and speed of seeding aircraft, and cloud ice whose number concentration is estimated from the mass of liquid CO<sub>2</sub> put into the grid box assuming that  $10^{13}$  ice crystals are produced while 1 g of liquid CO<sub>2</sub> vaporizes in clouds.

### **5.3 Hygroscopic seeding**

#### **5.3.1 Model studies using simplified dynamical frameworks**

As was pointed out above, parcel models are useful to study processes dominating the formation period of a cloud. Due to their simple dynamics, a sophisticated bin scheme can easily be coupled to study the interaction of hygroscopic seeding particles with the natural microphysics (Cooper et al., 1997; Caro et al., 2002; Segal et al., 2004 and Yamashita et al., 2015) They suggest that the seeding effects to promote raindrop formation of hygroscopic particles with submicron sizes are weak or negative as compared to those of hygroscopic particles with micron sizes.

Owing to the limitations of parcel models in representing the microphysical and dynamical properties of real clouds, their results need to be verified using multi-dimensional models with a sophisticated bin spectral microphysics scheme.

Kuba and Murakami (2010, 2012) investigated the effect of hygroscopic seeding on warm rain clouds using a hybrid cloud microphysical model combining a Lagrangian CCN activation model, a semi-Lagrangian droplet growth model, and an Eulerian spatial model for advection and sedimentation of droplets. They showed that the broadening (production of larger droplets) itself accelerates the onset of surface precipitation, but what is needed to increase the total precipitation is a decrease in the number concentration of cloud droplets (an increase in mean droplet size) due to hygroscopic seeding.

### **5.3.2 Two- and three- dimensional NHM**

Yin et al. (2000a) conducted numerical simulations using a two-dimensional slab-symmetric non-hydrostatic cloud model with a detailed treatment of both warm and cold microphysical processes in order to evaluate the effects of South African hygroscopic flare seeding on the enhancement of precipitation in convective clouds. They also suggested, similar to the results obtained by the simplified dynamics, that out of the full spectrum, the most effective particles were those with radii larger than 1  $\mu\text{m}$ , especially those larger than 10  $\mu\text{m}$ ; the particles smaller than 1  $\mu\text{m}$  always had a negative effect on the rain development.

With regard to hygroscopic seeding of warm clouds, the modulation of the initial cloud droplet size distribution and the subsequent changes of precipitation formed through cloud microphysical processes could be investigated using parcel models and some kinematic models that can deal with the swelling and activation of hygroscopic particles as CCN and diffusion growth immediately thereafter (i.e. competitive condensation growth among seeding aerosols and background aerosols acting as CCN). However, since the maximum supersaturation expected during one time step is diagnosed because of a coarse time step and cloud droplets are generated based on the number of aerosol particles to be activated at the supersaturation in the 3D models incorporating the usual bin spectral cloud microphysics parameterization, such 3D NHMs cannot accurately express the competitive condensation growth among background and seeding aerosols. There exist NHMs with bin spectral microphysics parameterizations that have prognostic variables for aerosol particles as CCN, but due to expensive simulation cost, few studies on hygroscopic seeding using such 3D models have been performed so far. There is also no study on hygroscopic seeding for convective mixed phase clouds.

Since the results of the kinematic model suggest that the rainfall augmentation by hygroscopic (salt MP) seeding is basically attributed to the decrease in the number concentrations of cloud droplets (the increase in mean droplet size) and subsequent enhancement of collision-coalescence process, the increase in rainfall can be evaluated with NHMs implementing usual bin spectral microphysics parameterizations or even bulk microphysical parameterizations if the reduction of cloud droplet number concentrations by hygroscopic seeding can be accurately predicted. However, it is also reported that for the hygroscopic flare seeding, the number concentrations of activated CCN (the number concentrations of cloud droplets) increase, but at the same time, the concentrations of cloud droplets with larger sizes also increase. As a result the onset of surface rainfall is accelerated due to the accretional growth of large droplets (raindrop embryo effect) although total surface rainfall does not increase or slightly decreases. It is also suggested that the interaction between precipitation that reaches the ground at an earlier time and airflow inside and outside the clouds may promote the formation of second-generation convective clouds.

Apart from hygroscopic flares and sodium chloride micro-powders, other materials include the combustion agents and anti-caking agents. However, the CCN and INP abilities of these agents and/or particles generated from them have hardly been investigated. Also, the influence of these particles on the microphysical structures of clouds is unknown.

## **5.4 Glaciogenic seeding**

### **5.4.1 AgI seeding**

Since early 1980s, silver iodide (AgI) seeding effects on strong convective clouds were investigated using a two-dimensional time-dependent cloud model which covers a region 19.2 km x 19.2 km with 200 m grid intervals (Hsie et al., 1980). The model traces the seeding agents, which advect and diffuse along the flow field and interact with the supercooled cloud fields through contact and deposition nucleation. Levin et al. (1997) showed the potential to augment precipitation by AgI seeding, which is closely related to the dispersion of the proper amount of seeding agent into the proper region and at the proper time to obtain optimum effects. Farley et al. (1994) implemented the AgI seeding scheme into a three-dimensional time-dependent cloud model and investigated the silver iodide (AgI) seeding effects on deep convective cloud.

Meyers et al. (1995) developed the seeding scheme based on laboratory studies of AgI particles (DeMott, 1995). The scheme deals with AgI particles in air as a prognostic variable and represents explicit ice initiation by AgI particles through four ice nucleation mechanisms. This scheme was applied to the simulation of an orographic precipitation event seeded with the specific aerosols on 18 December 1986 from the Sierra Cooperative Pilot Project (SCPP) using the Regional Atmospheric Modeling System (RAMS). The simulation suggested that precipitation enhancement occurred due to increased precipitation efficiency since no large precipitation deficits occurred in the simulation. This type of AgI seeding scheme has been used to investigate AgI seeding effects on convective clouds (Curic et al., 2007; Chen and Xiao, 2010, etc.) and on orographic clouds.

All cases are seeded in the region of the strongest updraft when the model cloud top was passing the -10 °C level, and they produce significant effects (by 20-30%).

Hashimoto et al. (2008) developed the AgI seeding scheme for the Meteorological Research Institute's non-hydrostatic model (MRI-NHM), which is similar to Meyer's (1995) scheme except for tracing AgI particles not only in air but also in hydrometeors. Therefore the immersion freezing nucleation can be much more realistically and accurately simulated. This scheme has also been implemented in the Thompson microphysics parameterization of the Weather Research and Forecasting (WRF) model and used to investigate AgI seeding effect on idealized orographic clouds. The sensitivity tests indicated that deposition was the dominant nucleation mode of AgI from simulated aircraft seeding, whereas immersion freezing was the most active mode for ground-based seeding. Deposition and condensation freezing were also important for ground-based seeding (Xue et al., 2013a). Recently this AgI seeding scheme has been used in many studies to investigate AgI seeding of orographic clouds (Xue et al., 2013b; Xue et al., 2014; Chu et al., 2014; Hashimoto et al., 2015; Chu et al., 2017a; Chu et al., 2017b; Xue et al., 2017), most of them using the WRF model in LES mode.

Xue et al. (2013b) used the model to simulate the ground-based and airborne AgI seeding of orographic clouds in southern Idaho during the 2010/11 winter season and found that airborne seeding is generally more efficient than ground-based seeding in terms of targeting, but its efficiency depends on local meteorological conditions and is inversely related to the natural precipitation efficiency.

Chu et al. (2014, 2017a, 2017b) and Xue et al. (2016) simulated orographic clouds under various atmospheric conditions and the effect of ground-based AgI seeding on them using WRF Model in LES mode. They validated the 100-m LES results against observed storm structures and the seeding effect on radar reflectivity. Furthermore, they find that dispersion from ground-based generators is very dependent upon turbulent mixing from wind shear and especially from thermal instability. In general, the effectiveness of seeding is found to be limited by the vertical dispersion of the seeding material. Seeding does not impact significantly on the dynamics of orographic clouds. The enhanced precipitation is found to arise from the deposition of water vapour on ice crystals formed from the seeding material.

Geresdi et al. (2017) studied the effect of glaciogenic seeding on precipitation formation in idealized orographic clouds using a 2-dimensional NHM (WRF) with a bin microphysical scheme. AgI particles are tracked not only in air but also in water drops to properly simulate the immersion freezing nucleation. They find that the bulk parameterization (which is much less computationally expensive than bin microphysics) is able to represent all the microphysical processes associated with natural and seeded clouds. Furthermore, their modelling suggests that, in stable conditions with stratus orographic cloud, ground-based seeding has no effect but aircraft-based seeding can enhance precipitation provided that the cloud-top temperature is warmer than about -25 C. The enhanced precipitation is due mainly to ice particle growth by vapour deposition. For convective cloud, the seeding impact was found to be sensitive to the background concentrations of CCN and INP. Both riming and deposition are important for precipitation enhancement in convective cloud. A key finding is that for both stratus and convective cloud the effectiveness of seeding is inversely related to the natural precipitation efficiency of the cloud. In particular, increases of more than 10 % in precipitation can be obtained if the natural precipitation efficiency is less than about 70 %.

#### **5.4.2 Dry ice seeding**

A scheme for simulating dry ice seeding in a numerical cloud model was developed and applied to convective clouds in the 1980s (Kopp et al., 1983). In the model dry ice pellets are treated as a prognostic variable and ice crystal production is simulated based on the sublimation rate of dry ice pellets in clouds.

Murakami et al. (2007) simulated the dry ice seeding of orographic clouds in central Japan and used a 2D NHM with simple dry ice seeding scheme, where the seeding effect was represented by the introduction of a seeding curtain with a prescribed concentration of cloud ice.

Hashimoto et al. (2008) developed a dry ice seeding scheme for 3D NHM. The treatment of dry ice pellets as a prognostic variable and the process of ice crystal generation during sublimation of dry ice pellets in clouds are the same as the scheme of Kopp et al. (1983), but the delivery of dry ice pellets from aircraft can be realistically and accurately simulated. Using this model, the effect of dry ice seeding on seasonal snowfall amount in the catchment was evaluated (Hashimoto et al., 2015).

### **5.4.3 Liquid carbon dioxide seeding**

Cloud seeding using liquid carbon dioxide was first numerically simulated by Guo et al. (2006). They compared cloud seeding of shallow convective clouds using liquid carbon dioxide and silver iodide and found that liquid carbon dioxide was more effective than silver iodide for cloud seeding at atmospheric temperatures between 0 C and -5 C. Seto et al. (2011) simulated liquid carbon dioxide seeding of wintertime shallow convective clouds over the Sea of Japan and compared the model results with radar observations of actually seeded clouds. As for AgI seeding, it is necessary to update the information on CCN and INP capabilities of seeding materials incorporated in the model based on the latest results of laboratory experiments. In the case of numerical simulation using a liquid cooling agent such as liquid CO<sub>2</sub>, it is necessary to re-examine the number of ice crystals generated when the unit mass of a cooling agent is vaporized in clouds. Particularly, because liquid CO<sub>2</sub> boils and vaporizes quickly (on the order of 1 second) before being dispersed over a wide area, the vaporization amount per unit volume of space becomes orders of magnitude larger than dry ice pellets. Therefore it is doubtful whether excess water vapour necessary for the generation and initial growth of the enormous number of ice crystals calculated from the vaporized amount of CO<sub>2</sub> can be secured in an actually seeded cloud. Thus, the conditions for high ice crystal formation rates should be carefully examined. The availability of excess water vapour for newly nucleated ice crystals might be a critical issue. Another issue is the number of ice crystals generated during the vaporization of liquid CO<sub>2</sub> in clouds. As for the generation of 10<sup>13</sup> ice crystals per 1 g of liquid CO<sub>2</sub>, which is assumed from its similarity to the vaporization of dry ice, there is no published experimental support.

Regarding the relative effectiveness of dry ice seeding and liquid CO<sub>2</sub> seeding, since seeding using liquid CO<sub>2</sub> was originally developed as a supercooled fog dispersion technology, which can be carried out from the ground, it is doubtful whether liquid CO<sub>2</sub> seeding is effective for convective clouds. Simulation results show that liquid CO<sub>2</sub> seeding was not superior to dry ice seeding even for a relatively quiet supercooled layered cloud, which is similar to a supercooled fog in nature (Hashimoto and Murakami, 2016).

## **5.5 Model validation and improvement**

Not only models used for precipitation enhancement research, but also models used for numerical forecasting and general atmospheric research are required to have high accuracy and high reproducibility of simulated phenomena. Simulation results such as seeding effects will be trusted by using such a model. Regarding airflow structures, thermodynamic structures, and cloud microphysical structures simulated by the models, it is necessary to verify the reproducibility of the models against the observations and to improve them as necessary (Ohtake et al., 2014; Xue et al., 2014). For the models used in precipitation enhancement research, it is also essential to verify and improve seeding schemes against observation results on responses of clouds and precipitation due to seeding. Observation results obtained using the latest technologies as reviewed in Chapter 4 would be valuable verification data of numerical models. It goes without saying that the seeding scheme itself should also be constructed based on experimental results such as characterization of seeding material.

## **5.6 Data assimilation**

In recent years, numerical simulations have rapidly improved in accuracy with the remarkable progress of computer technology. However, spatio-temporal forecast (prediction) errors due to the error contained in the initial values and uncertainties and/or biases of each numerical model cannot be ignored. Major forecast centres around the world assimilate surface observation data, aerological observation data, meteorological satellite data, etc. to create global analysis data and assimilate wind profiler, radar and surface meso-net observation data to create regional analysis data. Therefore, when running the regional non-hydrostatic models with such global or regional analysis data as initial/boundary conditions, the reproducibility by the models of the synoptic scale/mesoscale phenomena generally does not indicate any serious problem. In the future, as the precision of the operational forecasting models improves, the reproducibility of the synoptic scale/mesoscale phenomena in numerical seeding experiments is also expected to improve.

On the other hand, many challenges remain to accurately reproduce the spatio-temporal development of individual clouds and cloud systems. From the standpoint of disaster prevention, data assimilation using data from phased array radar, Doppler lidar, dense surface observation network has been attempted, aimed at accurate prediction of cloud systems that bring intense rain in a short time period. However, it should be noted that there are still many model uncertainties and much research is needed before the actually seeded cloud system and its response to cloud seeding can be accurately reproduced by numerical simulations.

## **5.7 Uncertainty of forecast results**

While there has been great progress in numerical modelling, there remain some outstanding challenges that directly affect modelling related to precipitation enhancement. Huang et al. (2015) show that the structure of the atmospheric boundary layer in the presence of clouds is not well simulated in numerical weather prediction models, leading to systematic biases in both the thermodynamic and microphysical structure of cloud layers. As discussed in Section 5.2.2, uncertainties in the interactions between cloud dynamics and microphysics lead to even more significant challenges in the simulation of precipitation. These systematic uncertainties, which can be reduced by improving model parameterisations, are separate from the chaotic uncertainties associated with observational errors and variations in known parameters. Both of these sources of uncertainty are currently managed through the use of ensembles.

### **5.7.1 Initial data ensemble**

In order to evaluate the influence of the error inherent in the initial conditions, which cannot be solved at present even by fully utilizing data assimilation techniques, the ensemble forecast (simulation) method, which runs the model with initial condition perturbations, has been used at the major forecast centres. There are a few cases where the ensemble simulation method was adopted in the field of precipitation enhancement research. However, it may be appropriate to consider the relative magnitudes of the forecast error due to the temporal and spatial development of cloud systems and that due to the error in the initial conditions.

### **5.7.2 Model ensemble**

Regarding the accuracy in reproducing microphysical structures of clouds and precipitation and the seeding effect on them, it is considered that the different cloud microphysical parameterizations and seeding schemes among the models cause a large difference in the performance of the models, so that it is thought that the multi model ensemble simulation using several different models may increase the reliability of simulation results.

## **5.8 Usage of numerical models in weather modification research**

Orville (1996) already suggested the usage of numerical models for various purposes in weather modification research, e.g. hypothesis development, assessment of seedability, experimental design, operational decision, project evaluation, and understanding of seeding effects. As he suggested, numerical models have recently been used in various types of precipitation enhancement research and applications. Typical examples of the usage are reviewed below (compare also Chapter 6).

### **5.8.1 Before field projects**

In many cases the necessity of water resources (demand) has determined the location of precipitation enhancement projects. However, before the start of precipitation enhancement projects, spatial and temporal distributions of precipitation and cloud water content (the occurrence frequency of clouds suitable for seeding) should be investigated using numerical models in addition to basic surveys of operationally available observation data (Ritzman et al., 2015). Preliminary results from numerical seeding experiments can be also used to assess the expected increase in precipitation when implementing the precipitation enhancement project (Hashimoto et al., 2008). Based on such information, the location and timing of the precipitation enhancement project should be considered.

### **5.8.2 During field projects**

As guidance for the implementation of aircraft seeding and/or ground-based seeding during research campaigns and/or operational projects, forecast experiments with numerical models can be performed using quasi real-time forecast results provided from the forecast centres as initial and boundary conditions. And the occurrence of seedable clouds can be predicted based on the cloud water content, precipitation amount, cloud top height (temperature), and cloud base height. In the JCSEPA, Wyoming, Idaho and UAE projects, forecast experiments have been carried out during the project implementation period, and the effectiveness of them has been ascertained (e.g. Hashimoto et al., 2017). Regarding wintertime orographic snow clouds, information on the seeding effects and optimum seeding method (seeding position and seeding rate) determined on the basis of results of numerical simulations were made in advance (Hashimoto et al., 2008). The guidance on optimum seeding position and expected precipitation increase in addition to suitability rank of seeding were also provided (Murakami et al., 2011) during the field campaign of JCSEPA.

### **5.8.3 After field projects**

Using observation data obtained during field campaigns, it is possible to validate and improve the model performance in terms of reproducibility of natural clouds and seeding effect. In this way, once a highly accurate and reliable model becomes available, it can be used to evaluate the seeding effect on precipitation throughout the season. Furthermore, in the precipitation enhancement project targeting orographic snow clouds, the influence of seasonal cloud seeding on the dam water storage through snowmelt from spring to early summer can be also quantitatively evaluated by combining the atmospheric model results with a snowpack, snow melting and runoff model (Yoshida et al., 2009). Examples of numerical models for the evaluation of seeding effects are also discussed by Cotton (2009).

It is also becoming possible to assess the impact on natural (atmospheric and hydrological) environments by seeding suitable clouds throughout the season. For example, the influence on precipitation or snow depth in areas other than the target area (dam catchment area) could be evaluated.

## **5.9 Conclusions and recommendation**

In recent years cloud modelling has made tremendous progress. Three-dimensional mesoscale modelling of entire cloud systems embedded in a large-scale flow has become a new standard, at least partly due to the availability of models like WRF. These models are driven by the output of NWP models, and their nesting capabilities allow us to zoom into a region of interest. Here, their grid sizes are now approaching LES values. Furthermore, multi-moment or bin resolved schemes have been coupled to these dynamics, providing interesting insights into the functioning of cloud systems. Unfortunately, the sensitivity of model results to variations in the microphysics parameterization is an outstanding source of uncertainty. The representation of the atmospheric boundary layer in a cloudy atmosphere is also a continuing challenge in weather prediction models.

- Model intercomparison projects that compare the performance of models among each other and with an observed situation are, thus, of utmost importance to understand the key parameters in microphysics and boundary layer parameterizations, improve them and increase our confidence in the model results. The “piggybacking” method (Grabowski, 2014, 2015) could provide here interesting additional insights.

Another major deficiency in most of the NWP models that currently limits their use for seeding simulation purposes: most of them do not take into account the ambient background aerosol population for the simulation of drop and ice particle nucleation. This aspect, however, seems essential as the seeding particles aim to override the impact of the natural particles, and, thus the competition between the two populations needs to be simulated.

- Consequently, the development and improvement of numerical models, which include not only seeding aerosol particles but also atmospheric aerosol particles acting as CCN and INP as prognostic variables are required. Especially how to parameterize ice nucleation capabilities of various atmospheric aerosol particles is an urgent issue, as well as ice multiplication processes.

Furthermore, even though LES resolutions begin to become available, NWP models can still not represent all the relevant processes over all scales, in particular for convective clouds. We still miss full physical understanding of all the relevant processes and the current computational resources are too expensive and slow to include a complete description of the physics on all scales. It implies that we are limited in our ability to make precise rain predictions. The challenge is getting exponentially harder for smaller time and space scales. Current rain predictions are fairly good in estimations of the chances for rainfall over scales of tens of km and days but apart from special cases in which external forcing (such as orographic barrier) tends to fix the cloud location, there is large uncertainty in the exact timing, location and intensity of rainfall. Current forecast models are quite skilful on the synoptic scale but the local translation of the dynamics, microphysics and thermodynamics into cloud properties and to precipitation production are limited.

- In particular, the capability of even bin microphysics to fully simulate the dispersion of a droplet distribution near cloud base is a further challenge for modelling related to precipitation enhancement.

Regarding glaciogenic seeding, numerical modelling of dry ice seeding and AgI seeding has come to a level that is of practical use while numerical modelling of liquid CO<sub>2</sub> seeding still has uncertainty.

- The number of ice crystals generated during the vaporization of liquid CO<sub>2</sub> in clouds has not been confirmed experimentally and the availability of excess water vapour necessary for the generation and initial growth of the enormous number of ice crystals calculated from the vaporized amount of CO<sub>2</sub> is unknown, because liquid CO<sub>2</sub> boils and vaporizes quickly (on the order of 1 second) before spreading over a large volume of air and the vaporization amount per unit volume of air becomes orders of magnitude larger than that of dry ice pellets. These issues need to be re-examined.

Almost all the model simulations show that the seeding effects to promote raindrop formation of hygroscopic particles with submicron sizes are weak or negative when compared with those of hygroscopic particles with micron sizes. Therefore salt micro-powder seeding is generally more effective than hygroscopic flare seeding for warm clouds. However, the hygroscopic seeding effect on surface rainfall depends on the type of clouds and type of seeding materials, and consistent results have not been obtained. There is little research on hygroscopic seeding using three-dimensional NHMs, and seeding schemes used in NHMs also need to be improved. Studies on hygroscopic seeding using 3D NHMs with bulk or bin spectral microphysics parameterizations, which also include the competitive condensational growth among seeding and background aerosols acting as CCN and activation of hygroscopic seeding materials as INP, are urgently needed.

- Current AgI seeding schemes are based on experimental results from the 1990s. There has been remarkable progress in research on the CCN and INP capabilities of aerosols since that time. Recent experimental results should be reflected in AgI seeding schemes, which recognize that AgI can also serve as a CCN.

Also, for hygroscopic seeding, it is necessary to take into consideration the CCN and INP capabilities of particles generated from the combustion agent of hygroscopic flares and of particles included in salt micro-powder as anti-caking agents.

For both glaciogenic (AgI, dry ice and liquid CO<sub>2</sub>) seeding and hygroscopic (salt micro-powder and hygroscopic flare) seeding, typical spatial resolutions of 1 km or several hundreds of metres for 3D NHMs are too coarse compared with the initial spatial extent (10 m) of seeding materials, and the advection/diffusion of seeding materials tends to be over-estimated. In order to overcome such weaknesses of NHMs, LES models have become popular recently.

- To further improve the accuracy in advection/diffusion of seeding materials and high concentration ice crystals generated by cloud seeding, the use of LES-scale model resolutions in 3D simulations is recommended.
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## **6. CATCHMENT-SCALE RESEARCH PROJECTS**

### **6.1 Introduction**

A key challenge for weather modification science is to demonstrate that precipitation enhancement effects found in individual clouds can be extended to enhancement of precipitation over areas comparable with water catchments and over at least seasonal time scales. That is, while it may be clear that the precipitation process in a cloud can be affected by techniques such as seeding with silver iodide, the economic and societal benefits are realised only by such effects acting over substantial areas and time periods. The focus of this section is on the description of projects that are carried out on space and time scales large enough to be of economic benefit. Clearly the actual benefit will depend upon the location and utilisation of any increase in the natural precipitation, and appropriate benefit-cost analyses should be carried out to justify such projects. Such confirmatory experiments should be carried out successfully before operational seeding is commenced. The experiments should be based on a range of exploratory experiments focused on the issues considered in Section 3 (Dennis, 1980).

Research projects can be coarsely identified as either exploratory or confirmatory. A range of exploratory activities should have been completed before commencing the design of a project aimed at catchment-scale impacts. The scope of such preliminary studies is discussed in Section 6.2. Clearly the scale and cost of catchment-scale projects mean that they should be designed as confirmatory experiments. Once it is demonstrated that the implementation of a catchment-scale project is justified on scientific and economic grounds, the project should be designed in a manner to account for the relatively low signal to noise ratio of most weather modification techniques, and this is discussed in Section 6.3. Not all clouds are suitable for seeding, and so clear seedability criteria need to be listed to ensure that seeding only occurs when suitable conditions prevail, as discussed in Section 6.4.

In order to unequivocally demonstrate an impact of seeding, it is essential to identify specific indicators of impact at the start of a project. The challenges associated with the specification of impact indicators to assess the results of a project are considered in Section 6.5. Any catchment-scale project will require a range of observations to determine when conditions are suitable for seeding, and to assess the results of seeding. The preparation of the required observing systems is discussed in Section 6.6. Although a project is carefully designed to produce enhanced precipitation in a specified area and time period, it is essential to ensure that there are no adverse effects of seeding within the overall region, and so Section 6.7 describes a range of environmental issues that should be considered within the project framework. The economic benefit of weather modification is discussed in Section 6.8, and the findings and recommendations are summarized in Section 6.9.

As was detailed in Chapter 3, the winter orographic seeding exploratory campaigns have generally yielded more encouraging results than projects on mixed phase/stratiform summer convection. While the latter still needs confirmation from further exploratory campaigns, the winter orographic seeding will be used as the main example of how to proceed to a confirmatory catchment project. Thus, the discussion in this section is focused on weather modification through the release of some seeding material (such as silver iodide particles) into

the clouds to cause the transformation of supercooled liquid water (SLW) into ice crystals, which in turn lead to enhanced precipitation on the ground. This focus is taken because so far the execution of catchment-scale experiments has been almost exclusively based on this hypothesis. The discussion, however, should be applicable to alternative techniques that have been shown to be feasible through preliminary (exploratory) studies, discussed in Section 6.2. Terblanche et al. (2000) consider the challenges associated with the identification of a statistically significant impact from the seeding of mixed-phase clouds. In particular, although significant impacts are observed by radar on seeded cloud systems, a significant increase could not be observed in the surface precipitation of the target area.

In recent years there have been three catchment-scale experiments described in the scientific literature. There were two phases of the Snowy Precipitation Enhancement Research Project (SPERP) in the Snowy Mountains of south eastern Australia, with SPERP-1 from 2005 to 2009 described by Manton et al. (2011) and SPERP-2 from 2010-2013 discussed in Manton et al. (2017). The Wyoming Weather Modification Pilot Project (WWMPP) ran from 2008 to 2014 at two sites in Wyoming, USA (Breed et al., 2014). Freud et al. (2015) describe the Israel-4 experiment, which commenced in northern Israel in 2013 and is expected to run for six winters. These three experiments provide the basis of the discussion in this section.

It is recognized that other catchment-scale experiments have been carried out recently in other countries. The Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) is being conducted in India (Prabha et al., 2011; Kulkarni et al., 2012) with a main focus on convective clouds and hygroscopic seeding from aircraft.

A long-term aircraft project on suppression of wildfires by inducing artificial precipitation above the fire targets has been carried out in Siberia and other Eastern parts of Russia from 1968 to 2007. After a 5-year delay and several disastrous wildfires, the project was started again in 2012, and during the next several years the relevant area will be significantly extended. The project utilizes glaciogenic seeding at the tops and cores of convective and stratus clouds. Statistically significant increases of precipitation from single clouds comparing with prognostic values are achieved in many cases (Danelyan et al., 2017). However, the results of those experiments have not yet been disseminated in refereed publications.

Precipitation enhancement activities in China started in 1958 (Yao, 2006; Guo et al., 2015). Along with the increase of social and economic demands and the rapid development of meteorology undertaking, there has been a significant development of precipitation enhancement activities since 1990s, designed for fighting drought, mitigation of water resources shortage, prevention and extinguishment of forestry fire, and improvement of ecological environments, etc.. Hundreds of precipitation enhancement projects have been carried out in different provinces in China during the past decades (Yao, 2006; Guo et al., 2015). Among these projects, there were two randomized precipitation enhancement experiments, one was implemented in Gutian Area of Chinese Fujian Province during 1974-1986 (Yao, 2006), the other has been carried out in four Chinese provinces (Shandong, Fujian, Hainan, and Jilin) since 2014, seeding with AgI based on rockets or aircraft. Some comprehensive precipitation enhancement projects, such as Stratiform Precipitation Enhancement Project in North China (1982-1990) (Yao, 2006), Chinese Weather Modification Project (2001-2005) (Yao, 2006; Guo et al., 2015), and Chinese Weather Modification Project

(2006-2010) (Guo et al., 2013; Guo et al., 2015), have played important roles in the improvement of comprehensive precipitation enhancement techniques in China.

Given the variegated history of weather modification (Fleming, 2010), it is important to emphasise that the detection of enhanced precipitation on the ground involves careful statistical analysis over many experimental units, which may vary from a few hours to a day or more. For such analyses to be statistically robust and efficient, it is essential that the experiment procedure is maintained consistently over the duration of the project. The scientist's inclination to modify an experiment as new knowledge is gained can be a great impediment to the successful outcome of a precipitation enhancement project.

## **6.2 Preliminary studies**

Preparation for a catchment-scale project typically starts many years before its main field stage. It is not unusual for a series of observing experiments to be carried out to characterise the clouds of the region of interest and to assess their suitability for seeding. For example, Warburton and Wetzell (1992) present exploratory studies of the suitability of clouds for seeding in the Snowy Mountains, Murakami et al. (2001) study the occurrence frequency of seedable wintertime orographic clouds in the central part of Japan, Koshida et al. (2012) report the occurrence frequency of various types of clouds that may be suitable for hygroscopic and glaciogenic seeding, and Geerts et al. (2010) describe exploratory studies in Wyoming. Exploratory studies on convective clouds during the Indian monsoon season have been conducted from 2009 and three phases of the experiment have been completed.

In addition to observations of the clouds and their environment, it is appropriate to carry out numerical modelling studies of the cloud systems to further assess their suitability for seeding. For winter orographic clouds, the modelling would need to confirm that SLW is generated at least on the upwind side of the mountain range. For mixed-phase clouds, the effects of the local aerosol distribution on the cloud microphysics would be explored, as well as the microphysical and dynamical processes associated with the development of precipitation.

Seeding material can be injected into clouds through a number of approaches, as discussed in Section 3. The actual approach used in a catchment-scale project will be determined by a number of factors, such as availability of infrastructure and seeding material. Independent of the specific approach to be used, it is essential to carry out background studies to ensure that the seeding material will reach the appropriate part of the clouds with a proper dosage in an appropriate time from release. The studies should involve both modelling and field trials. The modelling would establish that seeding material is reasonably expected to disperse from the source to the cloud. Field studies should document environmental conditions such as wind speeds, updrafts, wind shear, and cloud properties such as cloud base temperature, cloud depth, liquid water content near cloud base and cloud depth. Huggins et al. (2008) show that snow chemistry in SPERP-1 can be used to identify successful targeting of seeding material, providing a basis for confirming and calibrating the dispersion model.

When it is established that clouds suitable for seeding occur for a reasonable fraction of the time in the appropriate seasons, it is usual to carry out an analysis of the historical climate data to test whether the impact of seeding is expected to be detected in a reasonable time period (for example, Manton et al., 2011). The analysis involves a simulation of the likely

configuration of the project, so that past seedable events are randomly selected for "seeding". A "seeded" event has its observed precipitation increased by a specified fraction (such as 20 %), while the observed precipitation for "unseeded" events are unchanged. Statistical analysis of the "seeded" and "unseeded" events can determine the probability that the impact (say 20 %) can be detected. The probability of detection increases with the total number of seedable events.

A novel historical analysis was carried out by Morrison et al. (2009) on winter precipitation data in Tasmania where both experimental and operational cloud seeding has been conducted since 1960. Although the operational seeding does not include any randomization (and associated unseeded events), there are periods where there has been no seeding. Thus, it was possible to distinguish 146 months in which no seeding had occurred and 130 months where some seeding had occurred across the 46 years from 1960 to 2005. Careful analysis showed that precipitation in the catchment area in seeded months was statistically significantly enhanced by between 5 and 14 % compared with unseeded months.

There is comprehensive evidence of climate change occurring in many regions across the globe (IPCC, 2013). For example, Chubb et al. (2011) show that precipitation on the western slopes of the Snowy Mountains of south eastern Australia declined over a 20-year period and that the decline was associated with changes in the frequency and intensity of synoptic-scale systems. Wintertime orographic cloud seeding is carried out in these mountains and so, as in similar regions of the world, it must be anticipated that climate change will need to be taken into account as operational seeding continues.

### **6.3 Randomized design**

Precipitation falling from similar cloud systems can vary by more than 100 %. The actual effect of seeding an individual system is random, owing to the variability in both the environment of the cloud and the cloud itself. While the average impact of seeding may be an increase of 20 % in the natural precipitation, the impact on an individual cloud could even be negative. Thus, the signal to noise ratio is quite small in catchment-scale experiments. This observation also reflects the challenges in scaling up from more controlled cloud-scale experiments, where the individual cloud processes may be followed.

It is therefore clear that the design of a catchment-scale project needs to include a randomization process to select events to be seeded and events not to be seeded (unseeded). Because scientists are invariably involved in tactical decisions on the identification of seedable events, it is necessary to ensure transparency (as with medical trials) by not allowing the relevant scientists to be aware of the seeding sequence. Indeed it is desirable for the seeding sequence to be kept secret until after the initial analysis of the project data.

Based on the nature of the local precipitation as well as available infrastructure, it is necessary to define the duration of an experimental unit (EU); this is the period over which seeding will take place when the environmental conditions are suitable for seeding. For early experiments when only daily rainfall data were readily available, the duration of an EU was typically one to several days (for example, Smith et al., 1963). For more recent experiments when real-time precipitation is usually recorded and monitored, the duration of an EU is typically a few hours, recognizing the expected duration of consistent cloud conditions; for example, Breed et al.,

(2014) deduce that 4-hour EUs are appropriate for WWMPP. It is also important to recognize that the variability of natural precipitation increases with decreasing time scale, and so very short duration EUs will have rather large inherent variability.

A key aspect of the randomization is the specification of the seeding ratio; that is, the ratio of number of seeded events to the number of unseeded events. In order to optimize the amount of enhanced precipitation, it is not unusual to use a seeding ratio of 2:1, as in SPERP-1 (Manton et al., 2011). However, Manton and Warren (2011) note that a seeding ratio greater than 1:1 is likely to lead to the range of environmental conditions for unseeded events being smaller than for seeded events. This limitation means that, when unseeded events are used to estimate the natural precipitation (that is, precipitation in the absence of seeding) in seeded events, extrapolation rather than interpolation is required for some seeded events. It is well-known that extrapolation leads to greater statistical uncertainty than interpolation, and so recent experiments such as Israel-4 (Freud et al., 2015) and SPERP-2 (Manton et al., 2017) tend to use a seeding ratio of 1:1.

The aim of a catchment-scale project is to enhance precipitation in a target area of around at least 1000 km<sup>2</sup>. In most situations, the larger the area the more useful is the outcome. However, there can be challenges in ensuring that seeding material can be delivered over a large target area. The target area should be determined by the proposed application of any increase in precipitation. For hydrological applications, the target would be defined by the local catchment area.

In order to evaluate the impact of seeding in the target area, it is usual to identify a control area, which is essentially used to predict the natural precipitation in the target area. Two key conditions for a control area are that its precipitation is highly correlated with the precipitation in the target area (owing to similar environmental conditions), and that it is not impacted by seeding material. The first condition means that the control precipitation can be used to estimate the target precipitation, while the second condition means that the control precipitation always represents the natural precipitation of the region.

A range of target-control configurations has been used in the past. The two most common configurations are the fixed target and control (used in SPERP) and the crossover target and control (used in WWMPP). For the first, the control area is an upwind region that is well-correlated with the precipitation in the target and is not impacted by seeding material. For the second, two similar areas (generally lying at right angles to the wind direction) are used, with one being selected as target and the other as control for each EU. The crossover configuration has the theoretical advantage that fewer EUs should be needed to obtain a statistically significant result (Gabriel, 1999). However, the configuration has a practical challenge of identifying areas that have a high precipitation correlation (so that each can predict precipitation in the other) but where only one area is impacted by seeding material for each EU.

A third target-control configuration is to use a single target area (used in Israel-4), where randomization determines whether the target area is seeded or not seeded for each EU. The challenge for this configuration is to ensure that the synoptic environment and associated precipitation are equivalent across all seeded and unseeded EUs.

Thus a randomized design, which is needed to detect the relatively small impact of cloud seeding against the high variability of natural precipitation, involves a number of substantial decisions on the nature of the experimental procedure. In order for the statistical analysis of the results of the experiment to be robust (or even meaningful), it is essential for the experimental procedure to be maintained consistently over the duration of the experiment.

#### **6.4 Seedability conditions**

For recent cloud-seeding experiments, EUs tend to have a duration of no more than 24 hours, in the recognition that conditions suitable for seeding persist for a limited time as synoptic conditions evolve. It is therefore important to specify the environmental conditions that must be satisfied before an EU is commenced. These seedability criteria need to ensure that there is SLW that can be converted to ice crystals by the seeding material in the cloud. In turn, the ice crystals can grow and ultimately fall into the target area. Thus, the presence (or expected presence) of SLW is invariably a strict seedability condition for an EU to start.

To ensure that the seeding material properly interacts with the SLW, there are also conditions on the dispersion and targeting of the seeding material, with the specific conditions dependent upon the seeding strategy (as discussed in Section 3). These conditions usually include a range of wind direction at a certain level. For example, Freud et al. (2015) in Israel-4 require the wind at 850 hPa to be between 210 and 290 degrees so that aircraft-released seeding material is appropriately aligned with the local orography. The targeting conditions may also require a range of wind speed to allow for the mixing of seeding material from ground-based generators to a level where the seeding material activates ice nuclei. For example, Manton et al. (2017) in SPERP used a simple dispersion model (Rauber et al., 1988) to determine the allowable ranges of wind speed and direction to ensure appropriate dispersion and targeting. Breed et al. (2014) in WWMPP ran the Weather Research and Forecasting (WRF; Liu et al., 2008) model every 3 hours at 2-km resolution to support their seedability decisions. Also, the aerosol particle population of the ambient air needs to correspond to the selected seeding method, potentially excluding certain pollution scenarios for mixed-phase clouds.

With a randomized experiment, it is essential to ensure accurate targeting of seeding material in time as well as in space. In particular, it is necessary to have a buffer period between EUs to ensure that any seeding material from a specific EU has left the region before a new EU is commenced. For example, WWMPP specified a 4-hour buffer period, but SPERP used the dispersion model to determine the buffer period between EUs.

The dispersion of seeding material to interact with available SLW is the first step in ensuring that any enhanced precipitation falls into the target area. Seeding material such as silver iodide leads to ice nucleation at temperatures colder than about  $-5\text{ }^{\circ}\text{C}$ , and so it is usual to require cloud top temperatures to be less than about  $-8\text{ }^{\circ}\text{C}$  (Breed et al., 2014; Freud et al., 2015). Manton et al. (2011) in SPERP allowed a warmer cloud top temperature of  $-7\text{ }^{\circ}\text{C}$ , but then needed to add an additional criterion that the cloud depth above the  $-5\text{ }^{\circ}\text{C}$  level was greater than 400 m.

When seeding material is dispersed from aircraft, targeting is relatively straightforward and a seeding line is established at a suitable distance upwind of the target area. With fixed ground-based seeding generators, the turbulence in the boundary layer must disperse the seeding

material from each generator up to at least the  $-5\text{ }^{\circ}\text{C}$  level. Turbulent mixing is related to the stability of the boundary layer, and so the effectiveness of the dispersion of seeding material may be related to the Froude number of the low-level flow (for example, Watson and Lane, 2012). On the other hand, Manton et al. (2017) in SPERP find that variations in the Froude number for EUs (where the overall environmental conditions are similar by design) tend to vary with wind speed. Thus, Manton and Warren (2011) found that seeding from ground-based generators was not effective at low wind speeds, and so the seedability criteria in Manton et al. (2017) imposed a lower limit on the wind speed at the  $-5\text{ }^{\circ}\text{C}$  level.

By considering the ratio of seeded to unseeded precipitation in the target area, it is often implicitly assumed that the seeding impact is multiplicative. This assumption implies that there needs to be some natural precipitation during an EU which is enhanced by seeding. Indeed Freud et al. (2015) require a forecast of at least 0.2 mm over the following 24 hours for seeding to commence in Israel-4. Moreover, Manton et al. (2017) demonstrated from SPERP-1 that there was a negligible impact of seeding when the natural precipitation was low, and so it was required that some precipitation was falling at the time of commencement of an EU for SPERP-2. Related to this condition is the need for a forecast of seedable conditions to persist over the duration of the EU. Such forecasts are usually developed through analysis of numerical model results.

In addition to the seedability conditions to start an EU, it is usual to have specified conditions under which seeding should be suspended. For example, in SPERP, seeding was suspended if the reservoir storage was excessive or if severe weather was predicted for the region.

When the duration of an EU is only a few hours, detailed timing is important. Once a decision is taken to commence an EU, seeding commences (as soon as possible) at time  $t_s$ , and seeding continues until time  $t_s + d$ , where  $d$  is the duration of an EU. Owing to the need to purge the target of seeding material, the next EU cannot start until at least  $t_s + d + b$ , where  $b$  is the duration of the buffer period. While  $t_s$  gives the time at which seeding commences, it must be recognized that there is a delay between the start of seeding and the impact of seeding on cloud and precipitation. Thus in both SPERP and WWMPP the start of the evaluation period for an EU (during which seeding impact is assessed) is given by  $t_s + v$ , where  $v$  is 1 hour for SPERP and 0.5 hour for WWMPP. The evaluation period extends from  $t_s + v$  to  $t_s + v + d$ , and all indicators of seeding impact are evaluated over this period. It is clearly essential to ensure that seeding for a following EU commences after the end of the evaluation period, which means that  $b > v$ ; that is, the buffer period must be greater than the delay between the start of seeding and the start of the evaluation period.

## **6.5 Indicators of seeding impact**

### **6.5.1 Primary indicators**

A critical aspect of the design of a catchment-scale experiment is the specification of the indicators of a seeding impact, which are used to assess the success of the experiment. Given the wide range of observing systems and analysis methods available to scientists, many different indicators can be identified to measure and assess the many aspects of a large field experiment. However, the availability of many potential indicators of success leads to the problem of multiplicity, which is described succinctly by Hoaglin et al. (1985): "if enough

different statistics are computed, some of them will be sure to show structure". Mielke et al. (1982) note that multiplicity is a potential problem for cloud seeding experiments.

The problem of multiplicity is overcome by separating primary and secondary indicators. There are a small number of primary indicators that must be met at a specified level of statistical significance. There can be a list of secondary indicators that provide supplementary evidence for the physical basis of the primary indicators. Ideally the primary indicators should involve sampling across all EUs and should highlight the key aspects of a successful experiment. For example, Manton et al. (2011) specify only two primary indicators of success for SPERP-1: one related to the targeting of seeding material and the other related to precipitation enhancement. The first indicator was computed from snow chemistry analysis at 17 sites across the target area, and it was simply that the peak concentration of silver in the target is greater in seeded than unseeded EUs at the 5 % significance level. Given that preliminary studies (Section 6.2) should have shown that accurate targeting was likely during the experiment, such indicators are expected to be readily achieved, but they do highlight the physical basis of seeding.

The second indicator for SPERP-1 was that the fractional increase in precipitation in the target area due to seeding was positive at the 10 % significance level; the relaxation of the significance level below the usual 5 % level followed from the analysis of historical data (Section 6.2) that suggested only a 63 % probability of detecting a 0.20 precipitation enhancement at the 5 % significance level. Breed et al. (2014) note that a significance test controls only for false positive results, and so they add a requirement of a statistical power of 0.8 to control for false negative results for WWMPP.

The fractional increase in precipitation due to seeding is usually estimated by comparing the observed precipitation in seeded and unseeded EUs. Breed et al. (2014) provide a detailed discussion of the different indicators associated with different target-control configurations. For a single target configuration, the common indicator is the ratio of the mean precipitation in the target area in seeded EUs to the mean in unseeded EUs (SR). For a fixed target-control configuration, the indicator is the double ratio, equal to  $SR_t/SR_c$ , where  $SR_t$  is the single ratio for the target and  $SR_c$  is the single ratio for the control. Thus the  $SR_c$  adjusts the single ratio ( $SR_t$ ) to account for bias differences between seeded and unseeded EUs due to natural variability of precipitation.

For a basic crossover configuration, the indicator is the root double ratio, which is the square root of the product of the single ratios; that is,  $(SR_1 * SR_2)^{1/2}$  where  $SR_1$  and  $SR_2$  are the single ratios for each area. In this case, the unseeded area for each EU acts as a control for the seeded area. For WWMPP, the crossover configuration is supplemented by the addition of some control precipitation gauges. Consequently the appropriate indicator is the root regression ratio, equal to  $(SR_{t1} * SR_{t2})^{1/2} / (SR_{c1} * SR_{c2})^{1/2}$  where  $SR_{t1}$  and  $SR_{t2}$  are the target single ratios and  $SR_{c1}$  and  $SR_{c2}$  are the control single ratios.

The calculation of the various precipitation ratios depends upon the estimate of the mean precipitation across each area. Estimation of the mean precipitation gives rise to at least two sources of uncertainty. The first uncertainty comes from the measurement of precipitation, where significant under-catch of snow in gauges can occur in high winds. The second comes from the estimate of the area-average of precipitation, based on a number of measurements

at precipitation gauge sites. Manton et al. (2017) argue that, while such uncertainties will affect the quantitative details of the impact of seeding, they are not the major challenge to the estimation of seeding impact.

A major source of uncertainty is the assumption that the best estimate of the natural precipitation in the target area in seeded events is given by the precipitation in a control area (or in the target in unseeded events). An alternative (but equivalent) indicator to the double ratio of a fixed target-control configuration is obtained by using a linear regression equation to relate the target and control precipitation (Manton et al. 2011). For unseeded EUs, it is assumed that the precipitation in the target area ( $P_{tu}$ ) is given by

$$P_{tu} = a + b \cdot P_{cu}, \quad (6.1)$$

where  $P_{cu}$  is the precipitation in the control area, and  $a$  and  $b$  are regression constants. Assuming that Equ. (6.1) provides a valid estimate of the natural precipitation in seeded EUs, it follows that the increase in precipitation in the target area (residual precipitation) in seeded EUs is

$$R_{ts} = P_{ts} - (a + b \cdot P_{cs}), \quad (6.2)$$

where  $P_{ts}$  and  $P_{cs}$  are the target and control precipitation in seeded EUs. Thus the fractional increase in precipitation in the target area due to seeding is given by the sum of the residuals from Equ. (6.2) divided by the sum of the natural precipitations in the target over all seeded events; it is readily shown that the fractional increase is essentially equivalent to the double ratio.

Manton et al. (2017) show that the regression equation (6.1) does not provide a particularly close fit to the observations of the natural precipitation in the target area. Indeed it is well-known that the precipitation over mountainous regions is affected by the low-level stability and the wind speed (for example, Watson and Lane, 2012; Geerts et al., 2015). These effects are represented by the dimensionless Froude number ( $Fr$ ). A systematic search for the optimal predictors of the natural precipitation in the target area finds that additional variables, such as the Froude number or the wind speed, should be included in the regression equation (6.1). The optimal predictors lead to a reduction in both the root mean square error and the skewness of the fit of the regression equation to the observations.

Manton et al. (2017) further show that improved estimation of the natural precipitation in the target area leads to estimates of seeding impact with much greater statistical significance. An implication of the use of a more general regression equation for the natural target precipitation is that the seeding impact is not multiplicative, which is implicit with the use of a double ratio. Indeed, consideration of the spatial variation of the seeding impact across the target area suggests that the overall seeding impact is better indicated by the mean increase in precipitation per EU than by the fractional increase (incorporated in the double ratio). This result is consistent with direct observations by Reynolds (1988) and Super and Boe (1988) showing that seeding leads to increased precipitation of 0.1 to 1.0 mm/hr.

With the continuing improvement in the accuracy of mesoscale numerical models (Xue et al., 2013), it is tempting to use model output to estimate the natural precipitation in the target area (compare Chapter 5). However, the interactions between microphysics and dynamics extend over a huge range of space and time scales, and it is not yet feasible to fully represent all these processes in a model. While the models provide reasonably accurate estimates of precipitation on scales of tens of kilometres and several hours, there remain uncertainties in the precise timing, location and intensity, especially where convective processes are dominant. Nonetheless, with the application of a statistical adjustment to remove any model bias (for example, a simple regression between the observed and modelled target precipitation), a numerical model may provide a robust and accurate estimate of natural precipitation. However, this conjecture has yet to be confirmed through rigorous modelling experimentation.

### **6.5.2 Secondary indicators**

When the one or two primary indicators of seeding impact have been identified and documented, it is appropriate to list a number of secondary indicators, which should provide supplementary evidence of the physical basis of any seeding impact. For example, if the experiment includes snow chemistry observations, then comparing the dispersion of a passive tracer (such as indium oxide) with the distribution of silver iodide can be used to infer that seeding has affected the microphysical processes leading to increased precipitation on the ground (Chai et al., 1993). Manton and Warren (2011) find that the ratio of silver to indium in seeded EUs is much larger than one, suggesting that silver iodide has led to the enhanced nucleation of ice crystals.

In convective clouds, a strong microphysical signature has been found when using SF<sub>6</sub> as a tracer (Rosenfeld et al., 2010), supporting the methodology of salt seeding. However, the investigators state that “the significance of the accelerated warm rain processes in terms of changing rainfall amounts may vary in different conditions and require additional research that involves both observations and simulations”. On the other hand, hygroscopic flare seeding did not produce enough large particles to generate an identifiable seeded cloud volume. It is important that flares provide CCN larger than those that occur naturally in order to facilitate activation and condensation of water and to limit the number of activated droplets.

Especially in an experiment using ground-based generators, it is likely that the amount of released seeding material will vary from EU to EU owing to variations in wind speed and direction. In both SPERP-1 and WWMPP (Wyoming Water Development Commission 2014), it was found that there was little seeding impact when the amount of released seeding material was low. Manton et al. (2017, Figure 5) highlight this relationship through the use of diagrams that plot the accumulated precipitation residual (see Eq. 6.2) against the number of generator hours, with the residuals ordered (or ranked) by the number of generator hours. The ordered accumulated residual diagram shows that the seeded residuals are negligibly small when the number of generator hours is less than about 50 for SPERP-1. These diagrams readily show whether the seeding impact varies with the value of any external variable, such as cloud top temperature or wind speed and direction.

The list of potential secondary indicators is limited only by the range of observing systems available for an experiment. Particular emphasis should be placed on indicators that highlight systematic differences in cloud processes between seeded and unseeded EUs. For example, for

mixed-phase convective clouds, merging is an important process in the generation of precipitation, and so any attempts to evaluate the precipitation enhancement effects of cloud seeding must also include the issue of cloud mergers.

It is useful to distinguish between indicators based on data observed for every EU and those based on detailed data collected during special observing periods. For example, Miao and Geerts (2013) analyse aircraft data to identify changes in cloud microphysics due to seeding during some EUs of the WWMPP, while the ordered residual diagrams of Manton et al. (2017) use results from all EUs to identify systematic seeding impacts.

## **6.6 Observing systems**

The observing systems used in a catchment-scale experiment need to measure variables required:

- To satisfy the seedability conditions to determine when an EU may start (Section 6.4).
- To compute the indicators of seeding impact (Section 6.5).

It is therefore essential to have systems for the seedability conditions and the primary indicators that are extremely reliable, so that no seedable opportunities are lost and primary indicators are available for all EUs. The challenges associated with the observation of key variables are discussed in Section 4. Decisions to commence seeding are based on routine observations of the environment from sources such as local soundings, numerical weather prediction analyses and predictions, and satellite imagery, as well as more specialised measurements such as SLW. The key indicator of seeding impact is the precipitation over the target area which can be difficult to measure accurately in mountainous areas with wintertime snow or in areas with spatially-variable convective storms.

In cases where dry air entrainment can erode clouds rapidly (for example, convective clouds), real-time data on decision making and monitoring is difficult. There is a particular challenge in ensuring that the seeding material is delivered in the right place at the right time of cloud development. In the case of ground-based seeding generators, atmospheric stability and vertical profiles of winds must be observed to assess the convection in the boundary layer and dispersion of seeding material into the cloud. The expected fall-out region of precipitation also needs to be monitored.

## **6.7 Environmental issues**

By design, precipitation enhancement aims to alter the natural environment and so there is a potential for undesirable as well as desirable changes to the environment. Managing environmental risk is an important component of any catchment-scale experiment. Nearly forty years ago Dennis (1980) gave a critical analysis of the risks associated with cloud seeding, including toxicological, ecological, sociological and legal challenges. He noted an absence of evidence of environmental hazards, and this conclusion has been confirmed over the ensuing decades. For example, Lincoln-Smith et al. (2011) describe the processes that were carried out in SPERP to manage the potential risk of the seeding materials (particularly silver and indium) to the overall environment of the Snowy Mountains. Observations at even the generator sites showed the levels of seeding chemicals were well below any trigger levels for health concerns

and there was no indication of accumulated impacts over a five-year period. Abshaev et al. (2014) analysed results of measurements of AgI and PbI<sub>2</sub> in air, soil, water reservoirs and precipitation in regions with long-term (more than 40 years) implementation of artillery and rocket hail suppression technology (Northern Caucasus, Moldova and Georgia) beginning from 1964, and they found that the maximum concentration of these hazardous pollutants is several orders below the maximum allowable concentration specified by the World Health Organization. Moreover, Korneev et al. (2017) showed that the utilisation of silver iodide in aircraft seeding in Russian investigations did not lead to measurable increases in the level of these chemicals above the levels due to natural and anthropogenic sources. They suggested that seeding has extremely low impacts on the environment, and they did not observe any extra-area effects. Therefore studies conducted in Russia suggest that direct delivery of seeding materials into clouds has no ecological concern even after decades of implementation.

On the other hand, Fajardo et al. (2016) use laboratory studies to suggest that some biota could be adversely affected if "large amounts of seeding materials accumulate in the environment". Curic and Janc (2013) suggested the use of numerical simulations to estimate the spatial distribution of the fall-out of seeding material on the ground through wet deposition.

One of the potential environmental hazards of cloud seeding is the inherent redistribution of the natural precipitation over a region. While it is expected that precipitation is enhanced over the target area, neighbouring communities need to be assured that the impacts of seeding are negligible outside the target area. Given the historical difficulty in establishing a statistically significant impact of seeding over the target, it is clear that identifying significant extra-area effects is not straightforward. Curic et al. (2008) use a numerical model to suggest that seeding effects in a cumulonimbus storm (with a scale of about 40 km) can persist as the storm propagates downwind for about 100 km. However, this configuration does not relate to the seeding of winter clouds essentially fixed to orographic features. Moreover, in seeding mixed-phase clouds, the propagation of each cloud system is taken into account. Indeed results from Thailand suggest that the main effects of hygroscopic (Silverman and Sukarnjanaset, 2000) and glaciogenic seeding (Woodley et al., 2003) occur in clouds spawned by seeded mixed-phase clouds up to some hours after seeding. The issue of extra-area effects is discussed further in Section 3.4.

In relation to extra-area effects of seeding with silver iodide, there have also been reports that the effects of seeding may extend for days or longer both within the target area and downwind. It is suggested that the effects are due to the promotion of biogenic INP by silver iodide that reaches the ground (for example, Bigg, 1995). This effect is suggested to be related to the finding of Bigg and Miles (1964) of a relationship between rainfall and the concentration of INP at the ground. That result is consolidated by Huffman et al. (2013), who took measurements of aerosols and INP in a forest ecosystem and found high concentrations of biogenic INP during and for some hours after periods of rain. Soubeyrand et al. (2014) use statistical analysis to show that in southern Australia the rainfall before a major rainfall event is less than the rainfall after such events; that is, major rainfall events tend to start with heavy rainfall followed by an extended period of lighter rain. Linking this finding with the earlier results of Bigg and Miles (1964), they suggest that it follows that INP associated with the rainfall event induce the later rainfall. However, this suggestion does not recognize that rainfall in southern Australia is generally associated with the passage of synoptic fronts, which have

heavy rainfall during the frontal passage followed by steady rain after the main front has passed. Soubeyrand et al. (2014) find that this asymmetry is not observed in northern Australia, where the rainfall tends to be associated with local convective systems. Thus, the statistical correlation of INP and rain is more likely to be due to rain causing INP rather than INP causing rain.

Long (2001) gives a detailed discussion of some of the uncertainties associated with the persistence hypothesis. Moreover, the hypothesis would not seem to be consistent with the fact that statistically significant impacts of cloud seeding have been found over the period from 2005 to 2013 in the Snowy Mountains (Manton et al., 2017), using 5-hour EUs during the multi-day passage of winter fronts. Inter-annual variability of impacts during SPERP tended to be associated with large-scale climate variability rather than local influences.

## **6.8 Economic benefits**

The economic benefits of precipitation enhancement arise from the value of the increased water reaching the ground. That water will either feed directly into agricultural crops or more likely lead to increased runoff into regional hydrological systems. However, a major challenge for precipitation enhancement is that the physical processes extend across an extremely large range of spatial and temporal scales. It is important to consider all of these scales and how they interact when designing and evaluating experiments. The spatial scales range from sub-micron to synoptic scale while the temporal scales can range from microseconds to several hours or longer. One of the often-neglected issues in rainfall enhancement is the scaling up from the small to larger scales. It relates to the consideration, explanation and provision of proof - through each link in the chain of events, from the seeding intervention to more precipitation on the ground - in such a way that the end result has an acceptable impact with a desirable benefit-cost ratio. This challenge should be viewed in tandem to all the practical and logistical considerations when scaling up from single cloud experiments to area-wide impacts. The recent observations of French et al. (2018) provide substantial evidence of this chain of events for wintertime orographic seeding.

This issue is especially critical and difficult when dealing with convective clouds. Some of these issues were studied by Terblanche et al. (2000) during a semi-operational seeding experiment for rainfall enhancement in South Africa. The authors attempted to link the apparent positive storm-scale seeding effect to an observed larger-scale rainfall anomaly observed in the rainfall records in the area of seeding. However, simple calculations proved that there was a "two orders of magnitude challenge" between what could have been realistically expected from the seeding interventions on storm scale and what was observed in the area-wide rainfall records for the rainfall season. They concluded that the interventions and observations were probably unrelated.

Along similar lines, Terblanche et al. (2005) and Shippey et al. (2004) attempted to calculate the benefit-cost ratio of additional rainfall in a continuation of the semi-operational experiments in South Africa. For this purpose, they studied the storm climatology to estimate how many storms will have to be treated in a rainfall season to have the desired area effect, assuming that the storm effect they observed could be used as a basis for calculation. From these studies it became evident that rainfall enhancement could be more favourable than other options to address water stress in South Africa, but that there could be several logistical

challenges in treating the number of storms required, despite the fact that there appear to be sufficient candidate storms for treatment. As to be expected, the storm climatology revealed that the frequency of storm development is closely related to the diurnal cycle. As most storms develop in a short period of time in the afternoon (i.e. around the time when maximum surface temperature is recorded), the authors concluded that new, more efficient ways to deliver seeding material will have to become a priority for the future.

Silverman and Sukarnjanaset (2000) stated that it is unlikely that the current methodology of seeding individual mixed-phase clouds will be economically viable. However, even for winter orographic cloud seeding, careful calculation is needed to ensure that the benefit outweighs the cost. For both SPERP and WWMPP, the fractional increase in precipitation for seedable events is of order 15 %. But, seedable events generally make up only a fraction of the overall annual or seasonal precipitation. Moreover, the transformation of precipitation on the ground into hydrological streamflow incurs losses from for example evaporation and recharging of ground-water as well as delays as the water passes through the complex hydrological system. The relatively small precipitation signal and the complexity of the hydrological system mean that it is very unlikely that the impact of cloud seeding could be detected directly in measurements of streamflow or dam volume. Detailed rainfall-runoff modelling is needed to estimate the actual increase in annual streamflow due to cloud seeding. On the other hand, the increasing scarcity of potable water around the world means that the potential benefits of cloud seeding will continue to increase, while the costs should remain constant or decrease from technological and scientific advances.

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

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

## 6.9 Conclusions and recommendations

This chapter considers the challenges associated with the up-scaling of the research findings on precipitation enhancement discussed in Section 3 to provide evidence that the chain of physical processes can lead to enhanced precipitation over catchment-scale areas and time scales of seasons. Before commencing a large-scale experiment, it is essential to carry out a range of preliminary studies that demonstrate the suitability of the meteorological environment of the proposed site for sustained precipitation enhancement. Such exploratory studies are needed because the conditions for effective cloud seeding are quite demanding, and so suitable sites are limited geographically and by season.

- An important preliminary study involves the use of historical data to document the variability of precipitation and to estimate the time required to detect a statistically significant enhancement of the natural precipitation across the target area on a seasonal time scale.

Because the natural variability of cloud processes, including precipitation on the ground, is very large, careful design and management are needed to optimize the probability of detecting and confirming the physical basis of enhanced precipitation from cloud seeding. In order to detect the relatively small "signal" of enhanced precipitation against the large "noise" of natural variability on large time and space scales, randomized experiments should be carried out where the properties of specified seeded events are compared with those of similar but unseeded events. The comparisons are required not only on the amount of precipitation in seeded and unseeded events, but also on a range of properties that identify the sequence of physical processes that lead to any enhanced precipitation. The capabilities of observing systems at all scales from microphysical to synoptic are now very substantial, so that it is feasible to employ ground-based, aircraft-based and satellite-based instruments to systematically observe these physical (and chemical) properties.

For the statistical analysis of seeding impact to be robust and efficient, it is essential that a detailed protocol is prepared for the selection of events as seedable and for the seeding of randomized events. It is especially important that these protocols are followed precisely and consistently over the duration of the experiment. One aspect of the protocols is the accurate and consistent measurement of key variables such as the precipitation across the region of interest. Particularly for convective cloud, these measurements will involve radars, which must be routinely and consistently calibrated throughout the experiment.

The evaluation of a cloud seeding experiment needs to be based on a scientific understanding of the chain of dynamical and microphysical processes leading to enhanced precipitation on the ground. While the chain of processes for wintertime orographic cloud is now reasonably well understood, there remain substantial uncertainties in the processes associated with the enhancement of precipitation in mixed-phase convective cloud.

- These uncertainties mean that it is difficult if not impossible to fully evaluate a catchment-scale precipitation enhancement experiment on mixed-phase convective cloud.

Seeding agents such as silver iodide are formally toxic, but the quantity of external chemicals used in cloud seeding are generally too low to cause the levels of these chemicals in the environment to approach 'trigger' levels for health concerns. Nonetheless, it is important for any large-scale experiment to include careful monitoring and assessment of environmental risks.

A particular environmental risk arises from the potential for cloud seeding to cause the redistribution of precipitation at the ground in both space and time. While some cloud seeding activities are specifically aimed at redistributing precipitation (in particular, at reducing precipitation in some urban areas), there is little evidence that precipitation enhancement activities at a specific site lead to discernible changes in precipitation at downwind sites at the time of seeding or at later times.

Catchment-scale experiments invariably are aimed at demonstrating an economic benefit of cloud seeding. Because of the large variability of natural precipitation, such economic cost-benefit analyses are not straightforward, even for winter orographic cloud seeding where the cloud system and target area are clearly identifiable and fixed.

- However, scaling-up of the effects of seeding mixed-phase convective clouds remains an outstanding challenge, partly because of the uncertainties in the physical basis of the methodology but also because of the extreme variability of convective clouds in space and time.

The resolution of the substantial uncertainties that currently limit the scientific framework for cloud seeding, especially for mixed-phase convective cloud, will be accelerated through the publication of the data and results of relevant research in the international scientific literature.

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## 7. CONCLUSIONS AND RECOMMENDATIONS

In a period of accelerating climate change, the continuous struggle for reliable water resources has taken renewed urgency. A demand for precipitation enhancement efforts has been pronounced by numerous countries and has motivated the WMO Expert Team on Weather Modification to review the progress made since the last published assessments in a WMO workshop report (WMO, 2000) and a USA National Research Council report (2003). Then, the conclusions were cautious and an improvement of our fundamental understanding of crucial processes on clouds, precipitation, and larger-scale atmospheric functioning were recommended before any sound recommendations on precipitation enhancement itself could be made.

The current report is structured in five thematic chapters, and addresses the different topics in which progress has been achieved.

The first of these chapters summarizes the advances in our understanding of the natural atmosphere and the clouds it forms. It is now commonly accepted that the concept of an isolated cloud is not useful and the cloud has to be seen in a large-scale 3D context where the synoptic environment determines cloud formation and evolution on all scales. Large scale and local pollution determine the ambient aerosol population that provides the CCN and INP for the hydrometeors.

- Lack of knowledge still persists in particular associated with the ice phase, including the exact pathway of its formation via the INP, and the growth of hydrometeors due to their shape and density variability. Secondary ice multiplication processes need further investigation.

However, even though there still exists need for additional research to close our gaps of knowledge for some particular processes, it is accepted that the water loading of even the smallest clouds exceeds the mass of several commercial airplanes and the energy involved in the larger cloud systems exceeds those of the biggest weapons known to mankind. This image conveys the understanding that in order to initiate the chain reaction leading to precipitation from clouds or cloud systems on the basis of changing the mass or energy balance of the system would require tremendous and possibly dangerous efforts, while a precise knowledge of the system and careful intervention provide a more feasible strategy.

Seeding clouds with appropriate aerosol particles that augment or substitute for natural particles provide this "surgical" opportunity. The most promising results to date are found for glaciogenic seeding of wintertime orographic clouds by aircraft for clouds that already show a natural tendency to develop precipitation. Due to the larger variability of the dynamical conditions and to continuing uncertainties in the underlying mechanisms, the results for convective clouds are less conclusive. Those clouds can be seeded with glaciogenic or hygroscopic agents, which compete in different pathways with the natural particles. Here also, the location and timing of seeding inside the cloud is of utmost importance, and to intensify already forming precipitation seems to be the most promising approach.

The size, chemical composition, active temperature range (for INP) and concentration of seeding particles are important factors to control and the need for a supplementary role to the naturally present particle population was stressed. From our current understanding of hygroscopic seeding, it is necessary to ensure that the seeding particles are larger than the naturally-occurring aerosol particles, and this criterion may require the development of new types of seeding agents for flares. This chapter also describes other approaches of cloud modification like ionization and electrification, which do not have any clear scientific basis. Laser technologies are cited but even though they might succeed in forming cloud droplets in sub-saturated regions, these droplets could not grow to precipitation due to the overall lack of humidity. Cannons have been proven to be ineffective.

The development of observation methods has contributed considerably to our advances in the understanding of the functioning of clouds and their subsequent seeding, as is discussed in the following chapter. Radars with a range of different frequencies and other active or passive remote sensors are deployed not only on the ground but also on aircraft platforms and satellites. Research aircraft with sophisticated instrumentation allow probing of clouds in situ, and laboratory and wind-tunnel experiments have advanced our knowledge of small scale microphysical processes.

- Given the rapid evolution of remote sensing technologies, it is important to develop robust hardware and software systems that provide accurate and consistent estimates of the derived meteorological variables.

In Chapter 5 the progress in cloud modelling is discussed. Three-dimensional mesoscale modelling of entire cloud systems embedded into a large-scale flow has now become a new standard. These models are driven by the output of larger-scale models, and their nesting capabilities allow to zoom into a region of interest. Furthermore, multi-moment or bin-resolved schemes have been coupled to these dynamics and allow a much better (but still limited) understanding of the cloud microphysics.

- However, the sensitivity of model results to current microphysical schemes suggests that a series of model intercomparison projects should be used to identify the key microphysical processes and to optimise their representation.
- There remains the deficit that most schemes do not take into account the ambient background aerosol population for the simulation of drop and ice particle nucleation. This aspect, however, is essential in order to correctly understand the competing effect of seeded and natural particles and its development should be supported. The rapid evolution of computer capabilities should allow the simulation of such 3D mesoscale, microphysics and seeding processes within the next few years.

As detailed in Chapters 2-5, using cloud seeding to change the microphysics of a cloud at a specific geographical location is often a feasible strategy for changing the cloud dynamics and hence modifying its precipitation. However, in order to be beneficial in the context of an overall water shortage, the seeding needs to be extended to larger areas and time periods. Chapter 6 addresses this upscaling problem in proposing a strict protocol for the demonstration of the efficacy of a seeding activity for a catchment basin-sized region. Besides the

generalization of the scientific points already addressed in the other chapters, a particular concern is related to the cost-benefit aspect of the precipitation enhancement on catchment space scales and seasonal time scales. Furthermore, cloud seeding on these scales could have environmental risks that need to be managed by careful planning and monitoring.

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**Annex****LIST OF SOME PRECIPITATION ENHANCEMENT PROJECTS**

This list is an extension of the one from USA National Research Council (2003):

<i>Type of cloud</i>	<i>Experiment</i>	<i>Reference</i>
Winter orographic clouds	Snowy Precipitation Enhancement Research Project (SPERP-1 and SPERP-2)	Manton et al., 2011 Manton and Warren, 2011 Manton et al., 2017
	Tasmanian experiments	Ryan and King, 1997 Morrison et al., 2009
	Wyoming Weather Modification Pilot Project (WWMPP)	Breed et al., 2014
	SNOWIE: Seeded and Natural Orographic Wintertime clouds - the Idaho Experiment January 7 to March 17, 2017 [2 Doppler on Wheels mobile radars, the University of Wyoming King Air (UWKA) research aircraft equipped with cloud microphysical probes and airborne remote sensing platforms, including a W-band cloud radar and lidar, High-resolution snow gauges, Atmospheric soundings, Microwave radiometers, Vertically-pointing Ka-Band radars, Disdrometers, Remote Area Snow Sampling Devices (RASSD) to sample snow and trace chemistry, Acoustic Ice Nucleus Counter].	Geerts et al., 2013, 2017 Pokharel and Geerts, 2016, 2017 French et al., 2018
	Japanese Cloud Seeding Experiments for Precipitation Augmentation (JCSEPA) from 2006 -2011 drought mitigation and water resources management.	Hashimoto et al., 2008 Yoshida et al., 2009 Murakami et al., 2011 Ohtake et al., 2014 Hashimoto and Murakami 2016
	The Tokyo Weather Modification Pilot Project by MRI and Bureau of Waterworks of Tokyo Metropolitan Government October 2011 to March 2015 (Glaciogenic seeding, ground-based (AgI) or airborne seeding: Ground-based multi-wavelength, active passive remote sensing instruments, MRI cloud simulation chamber Aerosol instruments, CCN and INP counters, in situ aircraft measurements of aerosols, cloud and precipitation AgI particles from ground-based generators).	Araki et al., 2015 Tajiri et al., 2015

	Randomized Experiments from Israel (Israel-1: 1961–67, Israel-2: 1969–75 and Israel-3: 1975–95; Israel 4).	Levin et al., 2010 Freud et al., 2015
	Characteristics of orographic clouds and the evaluation of cloud-seeding experiment at Liupan Mountains in China (2018-2021) sponsored by National Natural Science Foundation of China, and executed by Chinese Academy of Meteorological Sciences and Ningxia Meteorological Bureau.	
	Orographic cloud-seeding experiment at Taihang Mountains in China (2017-2019).	
	2016 cloud seeding experiments Pyeongchang region of South Korea for precipitation enhancement Ground observation for cloud microphysical properties and the snowfall rates.	Chae et al., (2018)
Convective clouds Warm and mixed phase	Japanese Cloud Seeding Experiments for Precipitation Augmentation (JCSEPA) from 2006 -2011 drought mitigation and water resources management.	Kuba and Murakami, 2010 Yamashita et al., 2011 Kuba and Murakami, 2012 Koshida and Murakami, 2012 Murakami et al., 2011 Sakai et al., 2013 Yamashita et al. 2015
	Indian experiments	Murty et al., 2000
	The Queensland Cloud Seeding Research Programme 2008-09 and 2009-10.	Tessendorf et al. 2012
	United Arab Emirates Project for Rainfall Enhancement.	Semeniuk et al., 2014
	Randomized experiments on precipitation enhancement from clouds of different types (Ns-As, Ns, As, Ac, Sc, St) in Moldova and Ukraine (1970-1991).	Dinevich and Leskov, 2008
	Experiments on precipitation enhancement in Syria, Iran and Portugal by Central Aerological Observatory of Russian Hydrometeorological Service (1991-2000).	Dinevich and Leskov, 2008
	CAIPEEX (2009-continuing) Airborne seeding with flares and salt powder, in situ aircraft measurements of aerosols, cloud and precipitation, Ground based instruments: Dual polarized C-band radar, Wind profilers, Aerosol and CCN	Prabha et al., 2011 Kulkarni et al., 2012 Mahen Konwar 2012 Pandithurai et al., 2012 Padmakumari et al., 2013 Patade et al., 2014

	measurements, high density raingauge network, disdrometers, Microrain radars, surface fluxes and energy budget measurements, Flare testing laboratory, Aerosol measurements with CCN (Physical and statistical evaluation).	Patade et al., 2015 Varghese et al., 2016 Bera et al., 2016 Gayatri et al., 2017
	Chinese Randomized Precipitation Enhancement Experiment (CRPEEX) (2014-continuing), sponsored by Chinese Ministry of Science and Technology, and executed by Chinese Academy of Meteorological Sciences and local Meteorological Bureaus. (Rocket cloud seeding with AgI in Shandong Province, Fujian Province, and Hainan Province, Aircraft cloud seeding with AgI in Jilin Province).	
	Chinese Weather Modification Project (2006-2010), sponsored by Chinese Ministry of Science and Technology, and executed by Chinese Academy of Meteorological Sciences and local Meteorological Bureaus.	Guo et al., 2013 Guo et al., 2015
	Chinese Weather Modification Project (2001-2005), sponsored by Chinese Ministry of Science and Technology, and executed by Chinese Academy of Meteorological Sciences and local Meteorological Bureaus.	Yao, 2006 Guo et al., 2015
	Randomized Rain Enhancement Experiment in Gutian Area Fujian Province in China (1974-1986).	Yao, 2006
	Stratiform Precipitation Enhancement Project in North China (1982-1990), sponsored by Chinese Ministry of Science and Technology, and executed by Chinese Academy of Meteorological Sciences and local Meteorological Bureaus.	Yao, 2006

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Third WMO International Verification Workshop Emphasizing Training Aspects, ECMWF, Reading, UK, 29 January - 2 February 2007) (WMO TD No. 1391) (WWRP 2007-2).

WMO International Training Workshop on Tropical Cyclone Disaster Reduction (Guangzhou, China, 26-31 March 2007) (WMO TD No. 1392) (WWRP 2007-3).

Report of the WMO/CAS Working Group on Tropical Meteorology Research (Guangzhou, China, 22-24 March 2007) (WMO TD No. 1393) (WWRP 2007-4).

Report of the First Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), (Geneva, Switzerland, 23-25 April 2007) (WMO TD No. 1412) (WWRP 2007-5).

Report of the CAS Working Group on Tropical Meteorology Research (Shenzhen, China, 12-16 December 2005) (WMO TD No. 1414) (WWRP 2007-6).

Preprints of Abstracts of Papers for the Fourth WMO International Workshop on Monsoons (IWM-IV) (Beijing, China, 20-25 October 2008) (WMO TD No. 1446) (WWRP 2008-1).

Proceedings of the Fourth WMO International Workshop on Monsoons (IWM-IV) (Beijing, China, 20-25 October 2008) (WMO TD No. 1447) (WWRP 2008-2).

WMO Training Workshop on Operational Monsoon Research and Forecast Issues – Lecture Notes, Beijing, China, 24-25 October 2008 (WMO TD No. 1453) (WWRP 2008-3).

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1st WMO International Conference on Indian Ocean Tropical Cyclones and Climate Change, Muscat, Sultanate of Oman, 8-11 March 2009 (WMO TD No. 1541) (WWRP 2010-2).

Training Workshop on Tropical Cyclone Forecasting WMO Typhoon Landfall Forecast Demonstration Project, Shanghai, China, 24-28 May 2010 (WMO TD No. 1547) (WWRP 2010-3) (CD only).

2<sup>nd</sup> WMO International Workshop on Tropical Cyclone Landfall Processes (IWTCLP-II), Shanghai, China, 19-23 October 2009 (WMO TD No. 1548) (WWRP 2010-4).

5<sup>th</sup> WMO Symposium on Data Assimilation, Melbourne, Australia, 5-9 October 2009 (WMO TD No. 1549) (WWRP 2010-5).

7<sup>th</sup> International Workshop on Tropical Cyclones (IWTC-VII), Saint-Gilles-Les-Bains, La Réunion, France, 15-20 November 2010 (WMO TD No. 1561) (WWRP 2011-1).

Report of the Fourth Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 21-24 February 2011, (WWRP 2011-2).

WWRP/ETRP Workshop on Operational Monsoon Research and Forecast Issues – Lecture Notes, Beijing, China, 24-25 October 2008, (WWRP 2011-3).

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Proceedings of the 10<sup>th</sup> WMO Scientific Conference on Weather Modification, Bali, Indonesia, 4-7 October 2011(WWRP 2012-2).

Fifth Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 11-13 April 2012, (WWRP 2012-3).

Second WMO/WWRP Monsoon Heavy Rainfall Workshop, Petaling Jaya, Malaysia, 10-12 December 2012 (WWRP 2013-1).

International Workshop on Unusual Behaviour of Tropical Cyclones, Haikou, Hainan, China, 5-9 November 2012 (WWRP 2013-2).

Abstracts of Papers for the Fifth WMO International Workshop on Monsoons (IWM-V), Macao, China, 28-31 October 2013, Hong Kong, China, 1 November 2013 (WWRP 2013-3).

Second International Conference on Indian Ocean Tropical Cyclones and Climate Change (IOTCCC-II), New Delhi, India, 14-17 February 2012 (WWRP 2013-4).

WMO/WWRP International Workshop on Rapid Changes in Tropical Cyclone Intensity and Track, Xiamen, China, 18-20 October 2011 (WWRP 2013-5).

5<sup>th</sup> International Verification Methods Workshop, Melbourne, Australia, 5-7 December 2011 (WWRP 2013-6).

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Sixth Session of the Joint Scientific Committee (JSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 18-19 July 2013 (WWRP 2014-1).

Joint Meeting of the THORPEX International Core Steering Committee (ICSC) and the World Weather Research Programme (WWRP) Joint Scientific Committee (JSC), (Geneva, Switzerland, 17 July 2013) (WWRP 2014-2).

Workshop on Communicating Risk and Uncertainty, Melbourne, Australia, 26-27 July 2012 (WWRP 2014-3).

International Conference on Opportunities and Challenges in Monsoon Prediction in a Changing Climate (Pune, India, 21-25 February 2012) (WWRP 2014-4).

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6<sup>th</sup> International Verification Methods Workshop, New Delhi, India, 13-19 March 2014 (WWRP 2014-6).

Pre-Workshop Topic Reports Eighth WMO International Workshop on Tropical Cyclones (IWTC-VIII) Jeju, Republic of Korea, 2-10 December 2014 (WWRP 2014-7).

Proceedings of the 5<sup>th</sup> International Workshop on Monsoons, Macao, China, 28-31 October 2013, Hong Kong, China, 1 November 2013 (WWRP 2015-1).

Seventh Session of the Scientific Steering Committee (SSC) for the World Weather Research Programme (WWRP), Geneva, Switzerland, 18-20 November 2014 (WWRP 2015-2).

8th International Workshop on Tropical Cyclones (IWTC-VIII), Jeju, Republic of Korea. 2-6 and 10 December 2014 (WWRP 2015-3).

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For more information, please contact:

**World Meteorological Organization**

**Research Department**

**World Weather Research Programme**

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Tel.: +41 (0) 22 730 81 11 – Fax: +41 (0) 22 730 81 81

Email: [cpa@wmo.int](mailto:cpa@wmo.int)

Website: [http://www.wmo.int/pages/prog/arep/wwrp/new/wwrp\\_new\\_en.html](http://www.wmo.int/pages/prog/arep/wwrp/new/wwrp_new_en.html)