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General document on common questions and answers on cloud seeding

(Picture: Hygroscopic seeding near the cloud base with burn-in-place flares)

Thara Prabhakaran, Gayatri Kulkarni, Neelam Malap, Sudarsan Bera, Abhishek Gupta, Mahen Konwar, Shivsai Dixit, Shibani Bhatt, Mercy Varghese, B. Jayarao, P. Murugavel

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Abstract
This is a general document on common questions and answers on cloud seeding

Summary
Cloud seeding has been a topic of interest for many years for researchers as well as common people. It is an effective technique used to increase precipitation in a water scarcity area to boost agriculture and the economy. This document gives the history of cloud seeding in India, covers information about cloud seeding in layman's terms, and answers most of the questions that occur in the minds of common people, administrators, and policymakers.

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General document on common questions and answers on cloud seeding

IITM Report 2023

PREFACE

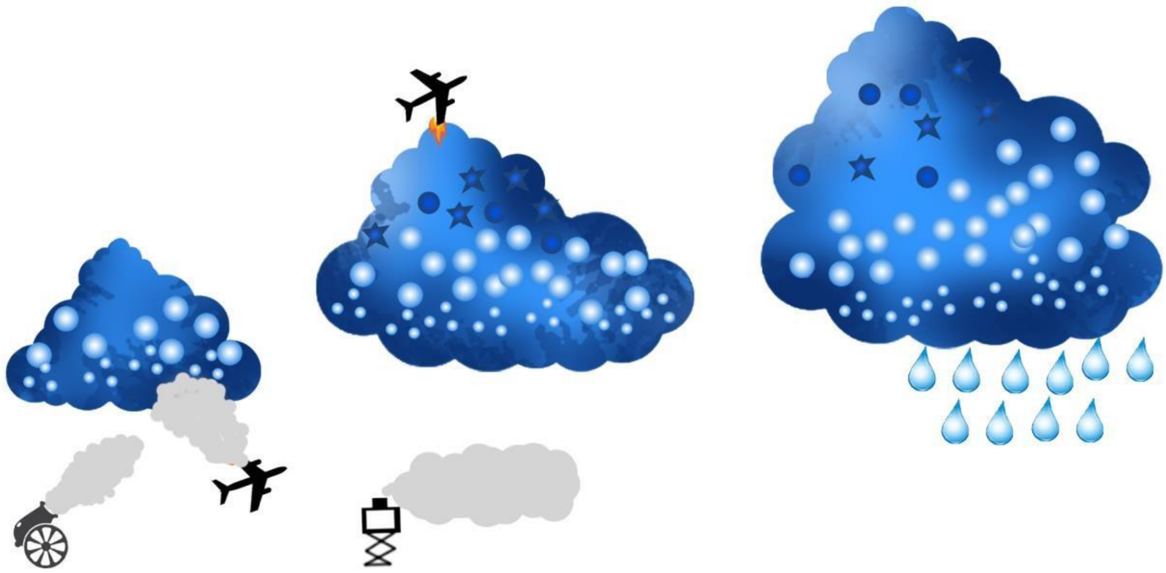
This document contains commonly asked questions and answers about cloud seeding.

This document is prepared by the CAIPEEX Team, which is involved in the research studies on aerosol-cloud interaction and precipitation. We hope this document will be helpful to those who are interested.

1. What is cloud seeding?

Cloud seeding is a 75-year-old technique (the first pioneering attempts were documented by Schaefer 1946 and Vonnegut 1947) used to modify suitable clouds with 'seed' particles to increase rainfall. These seed particles are 'cloud condensation nuclei (CCN), a particle on which water vapour condensates' or 'ice nuclei particles, a particle on which water freezes', a subset of suspended particulates in the atmosphere named aerosol particles. These CCNs have an affinity for water vapour to form cloud droplets. The ice nuclei particles can form ice particles.

Typically an aircraft is used to dispense these particles near the cloud base or cloud top. Cloud base seeding is where particles are released below the base of *cumulus clouds* (appear as a cauliflower) that have a warm base (the temperature of the cloud base is warmer than zero degrees). Cloud top seeding is done in cold clouds (where the temperature is below zero degrees). Warm cloud base seeding is called hygroscopic seeding and cold cloud seeding is called glaciogenic seeding.



Cartoon of the hygroscopic and glaciogenic seeding.

2. What are the types of cloud seeding?

- **Hygroscopic seeding:**

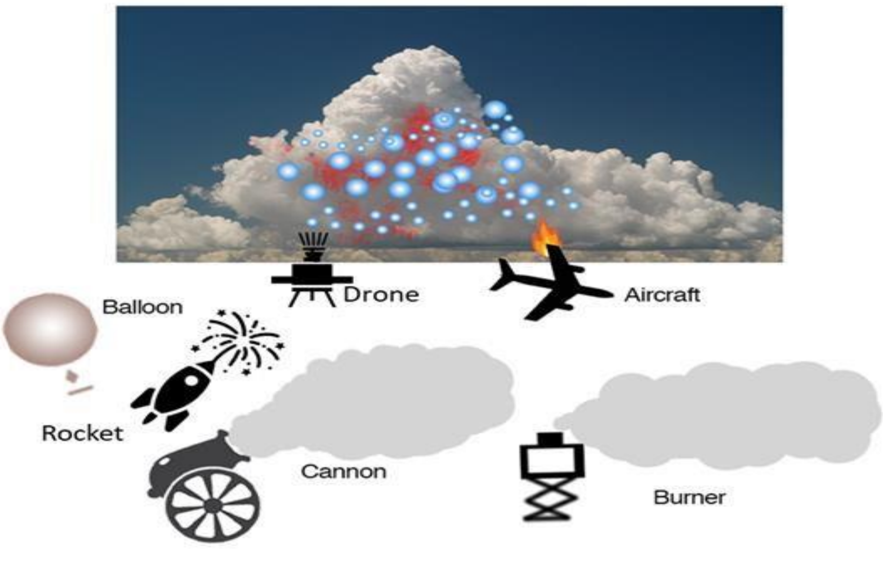
  In warm clouds, sodium chloride (NaCl), potassium chloride (KCl), or calcium chloride ($CaCl_2$) is used as a seeding agent, and this method is called Hygroscopic cloud seeding. In hygroscopic seeding, coalescence (drop spectrum broadens and during the nucleation process by seeding with larger than natural CCN of 0.5 µm to 3 µm dry diameter) of water droplets is promoted to improve the efficiency of rain formation.

- **Glacigenic seeding**: In a cloud with a temperature below freezing ($0^{o}C$), typically, silver iodide (AgI) is used as the seeding agent, and the seeding method is called glaciogenic seeding. The idea is to trigger ice production in supercooled clouds and enhance precipitation. The seed particles (AgI pellets) will act as sites where water in the subzero temperatures (supercooled water) deposits and forms ice crystals. These ice crystals grow by depositing more water as well as colliding with other ice crystals falling from above. They further fall through the warmer temperatures and melt to form raindrops.

Typically cloud seeding is done with flares (pyrotechnic material together with a burning agent which is compressed inside a tube encase) attached to the wings of an aircraft. These flares dispense the seeding material at the cloud base or within clouds.

3. How is cloud seeding done? What is the effective way of dispensing seed particles in the clouds?

Cloud seeding is done by burning flares near the cloud base or within the cloud. Flares and ground-based burners or ground-based artillery are used in various countries for cloud seeding. Ground-based systems are reported to be less efficient in introducing seed material into clouds. The most efficient way is using an aircraft equipped with flares on its wings (called burn-in place: BIP) and below the fuselage (ejectable: EJ). The major problem with artillery firing from the ground is that often the target cloud is missed, especially when the clouds are small, and updrafts are in a narrow region. The ground-based flares may be applicable if the cloud bases are closer to the ground. The released seed particles from the ground-based burners get dispersed in the boundary layer and may also form an environmental issue. In the case of airborne seeding, the cloud seeding flares are fitted in the racks attached to the wings of the aircraft and are the most effective way to dispense seed particles at the cloud base.



Different seed dispersal methods (Rockets, artillery, drone or aircraft mounted flares, ground-based flares or burners and balloons)

4. What type of seed particles are required for cloud seeding?

Hygroscopic flares contain sodium chloride or calcium chloride, producing small salt particles in the size range 0.1-1 micrometer diameter. The flares are in cardboard containers (12 cm long 7 cm diameter) and get triggered while attached to the wings. The Glaciogenic flares are in thin tubing containing ice-nucleating Silver iodide (AgI), which can form ice particles in clouds. The linear burning rate of the flare is ~ 0.66 mm per second.

5. What is the physics of cloud seeding?

Aerosol particles are suspended particles in the atmosphere. Some of the aerosol particles that have an affinity for water vapour are called cloud condensation nuclei (CCN). Cloud droplets are formed by CCNs present in the atmosphere. Cloud seeding is done in an existing cloud with large enough particles that can form larger cloud droplets. Rain forms in warm clouds when these larger cloud droplets collide and coalesce with other droplets. As the size of the drops increases, they start falling within the cloud body. The falling drops collide with other drops on their way down and coalesce to form a bigger drop. The raindrops, thus formed, fall out of the cloud base.

During the cloud seeding, the hygroscopic nuclei dispersed at the cloud base are expected to form larger cloud droplets than in a naturally developing cloud. The hygroscopic flares provide larger CCN than naturally available. Water vapour condenses on these particles readily. These droplets further grow by collision and coalescence with other droplets and accelerating rain formation.

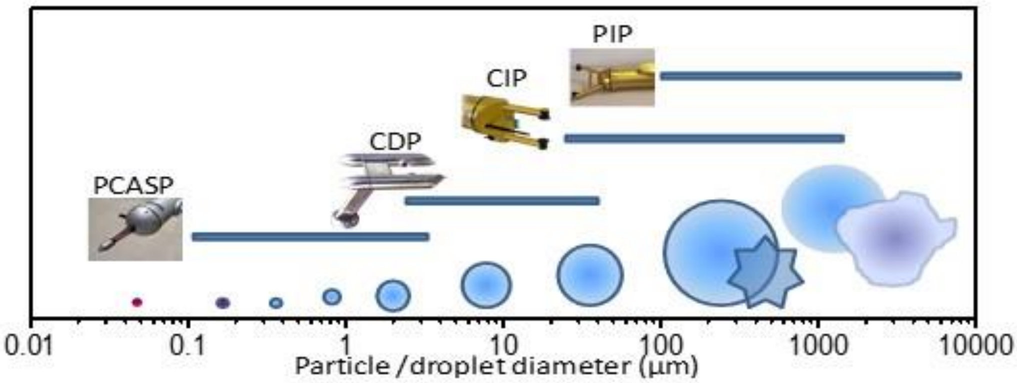
Cloud seeding is also done in cold clouds with glaciogenic particles, which can form ice particles. The ice particles thus formed will grow by accumulating water as well as ice or colliding with other ice particles. They journey to the ground as they are heavy and fall through the melting region. At temperatures warmer than zero degrees, these ice particles will melt and produce raindrops. In monsoon clouds, a combination of warm and cold rain processes is important.

6. How can one identify growing clouds?

Clouds that are not precipitating and have a level and clear cloud base, can have upward motion at the base of clouds and within the clouds may be considered. The water content in the clouds will also be large. These cloud properties are considered for choosing seedable clouds.

7. How to know about the cloud properties?

Cloud and rain properties are determined through various observations such as instrumentation placed on aircraft, radar, satellites and surface observations (automatic rain gauges, disdrometers etc.). Each of these observations has advantages and disadvantages. The aircraft measurements of clouds give microstructure of clouds, i.e. information on the cloud droplets (a few tens of micrometers), drizzle (a few hundreds of micrometers), ice particles (from a few tens to hundreds of micrometers), and raindrops (a few millimeters). These are measured with the help of scattering or imaging principles. The range of cloud droplets to the raindrop measurements requires 3-4 instruments, depending on the details required.



The different instruments (spectrometers) used on the aircraft to monitor tiny dry aerosol particles to cloud droplets of different sizes, rain and drizzle drops and ice particles of different sizes. The picture of instruments is also given in the figure.

Satellite measurements give bulk parameters for understanding clouds over a large, cloud microstructure (e.g. effective radius which is a geometric measure of the cloud droplet size) along with temperature, which is useful for inferring information about different precipitation formation processes. Radars (such as C-band polarimetric Doppler weather radar) can give information on reflectivity (which is a measure of the size of drops/ice particles in the cloud), condensed water content or ice water or rain water in the cloud, etc can be determined. These parameters are quite useful in understanding clouds and their ability to make rain and also to understand how much radiation they reflect, or whether they have the ability to make lightning and severe weather.

8. Does cloud seeding work? and for which type of clouds? Is there any evidence?

Typically, orographic clouds (over mountainous areas with a natural lifting process) and convective clouds (having convective updrafts) are selected for seeding.

There is extensive scientific literature on glaciogenic seeding in orographic clouds (World Meteorological Organization has released a review in 2018). These studies mainly come from the mid-western USA and illustrate that glaciogenic seeding can lead to a chain of processes leading to precipitation in the clouds. The clouds under orographically forced lifting are considered on the windward side of mountain ranges for seeding. These clouds from the Mid-western USA with active mixed-phase and ice processes were targeted for cloud seeding. The additional lifting due to orography is an added advantage to generating supercooled liquid water, which supports ice hydrometeor growth in these clouds. Snow enhancement through glaciogenic seeding is well established in the USA in the SNOWIE (Seeded and Natural Orographic Wintertime Clouds: the Idaho Experiment) cloud seeding research and operational study.

Cloud seeding is also conducted in suitable clouds when there are growing clouds (cumulus or deep cumulus or embedded convection in the upper-level stratus clouds or in the deep convective clouds) during their growing stages. The availability of clouds is a basic requirement. CAIPEEX has conducted exploratory experiments for glaciogenic seeding in convective clouds.

9. Is moisture availability important for Cloud seeding?

Moisture availability is very important for cloud seeding. The moisture is available through advection, evaporation etc. In a dry atmosphere, the cloud parcels must travel to a higher altitude to condense. As a parcel of air rises, it expands and cools. The cooling will continue until a temperature is reached where the air gets saturated. The saturation means that available water vapour in the atmosphere can condense onto a surface (An example is the condensation formed on the outer surface of a glass filled with ice-cold water. This is the water available in the air surrounding the glass, which has condensed on the glass surface as the air close to the glass surface is cold and saturated (with 100 percent humidity).

When there are more moist conditions, the cloud can form at a lower altitude (notice the clouds during the monsoon season) and at a higher altitude during dry conditions. This fundamental difference is important for cloud seeding. If the base of the cloud is situated at a greater altitude very close to /below the zero-degrees temperature, hygroscopic seeding may not be applicable. Glaciogenic seeding is more suitable in cold clouds.

10. Under which conditions will Cloud Seeding work?

There needs to be an optimum level of instability (convection) in the cloud, and the atmosphere needs to be moderately humid. These conditions provide vertical growth of clouds. However, if the horizontal winds are too strong, clouds may not grow tall and will be carried by the wind.

11. How can we quantify the efficacy of Cloud seeding?

The general understanding is that clouds cannot be modified operationally unless their natural precipitation processes are well understood and until we can measure a seeding effect with the seed particle of choice (This means that the efficacy of cloud seeding cannot be established operationally until natural precipitation processes are not understood, and is a prerequisite for any assessment of rain enhancement). This demands that Weather modification should have a sound scientific basis.

There are several ongoing research programs, as well as operational cloud seeding programs around the world, trying to quantify cloud seeding efficacy. Complete documentation of clouds with radar and ground-based rain gauges or snow gauges is a requirement for the quantification of cloud seeding. Continued observations over several seeded and unseeded clouds and their characteristics, such as rainfall, depth of clouds, rainfall area, liquid content in the cloud, etc., are crucial to documenting the efficacy. Randomized double-blind experiments are conducted in CAIPEEX.

12. What is the history of cloud seeding in India?

Indian Institute of Tropical Meteorology conducted a cloud seeding experiment in the '70s, during which no definite conclusions could be made on the efficacy of seeding towards precipitation enhancement. Though statistically not significant, early experiments suggest enhancement of rainfall due to seeding by 17% (Kapoor et al. 1974); while other experiments were inconclusive (Krishna et al. 1974), introducing significant uncertainty in the outcome of seeding.

Murthy et al., (2000) conducted cloud seeding experiments over 100 km inland from the west coast of India during June-Sept 1973-74, 1976, 1979-86; over an 11 year period cloud seeding. The experiment was done by area randomization of two 1600 km^2 target areas (north and south) separated by a buffer area, the size of each area being 1600 km^2. Salt seeding of stratocumulus and cumulus clouds were done and to 200-300m above cloud base observations were done. The salt seeding was done in 30 kg on a 3 km flight track. Results depended on cloud thickness, liquid water content in clouds. Certain conditions produced an increase in rainfall of 24% at 4% level. It was found that hygroscopic particle seeding accelerated collision coalescence.

Since 2003, operational cloud seeding programs by various state governments (Gujarat, Maharashtra, Karnataka and Andhra Pradesh, Tamil Nadu) have been conducted. All experiments in the past are based on area seeding and do not apply to the approach of isolated cloud seeding and are challenging to make conclusions.

Cloud Physics and weather modification research experiments in India (Ref. 50 years of IITM by D. R. Sikka and IITM publications)

1955: Rain and Cloud Physics Research (RCPR) was established at the Council of Scientific and Industrial Research (CSIR), New Delhi

1967: The RCPR transferred to IITM, Pune in 1967 and the following developments took place at IITM

- Laboratory studies and field studies on the microphysics of clouds and precipitation mechanisms in tropical monsoons
- The study of warm cloud modification for enhancement of rain
- Laboratory experiments for ice nucleation, freezing of water drop under supercooling conditions and ice multiplication in supercooled clouds.
- Identification of seeding material and their efficiency for the collision-coalescence of water drops under the influence of an electric field
- The role of the electric field in precipitation formation was attempted with laboratory experiments.

1968 – 1975 Cold Cloud Seeding Experiment during winter seasons using Silver Iodide as a seeding agent and radar observations of aerial echo-coverage and echo height of clouds within 50 km around Delhi. The analysis based on echo height indicated 11% increase in rainfall as a cumulative result and was statistically significant.

1973 and 1977 ***Thirunallar*** (near Chennai) field experiment during the SW and NE monsoon seasons based on using ground-based generators, results were not significant for rain enhancement.

1973-1985 Pune Aerial experiment for warm cloud seeding to assess seedability criteria for possible rain enhancement. The seeding under a randomized process using sodium chloride powder as the seeding agent. The experiments were inconclusive regarding the efficiency of warm cloud seeding for rain enhancement. However, seedability criteria were identified. The potential for enhancing rain was found to be higher for aerial cloud seeding systems.

The following state Governments have undertaken operational cloud seeding

- 2012 Three river basin project in Karnataka state
- 2003-2016 Andhra Pradesh Cloud seeding
- 2017, 2019 Varshadhaare project in Karnataka state
- 2019 Maharashtra Rainfall Enhancement Project

13. What is the research program CAIPEEX?

Considering the national demand for operational cloud seeding, with a view to relieving stress on water resources, IITM/MoES has started a national field experiment named Cloud Aerosol Interactions and Precipitation Enhancement Experiment (CAIPEEX) to advance research on the role of cloud and aerosols and cloud-radiation feedback on the physics of rainfall and microphysics of clouds.

Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) was formulated with the understanding that monsoon rainfall is heterogeneous in space and time and in spite of existing rain-bearing clouds, several locations in India experience drought conditions during the monsoon season. The CAIPEEX program benefited from the recent technological advances of airborne observational capabilities to monitor cloud and aerosol microphysics. The basis for cloud droplets and raindrop formation and how aerosol pollution influences these processes have been addressed in CAIPEEX. The two main objectives of the CAIPEEX program were a) to address the physics and dynamics of aerosol cloud-precipitation interactions and b) to formulate a scientific basis for aerosol-cloud interaction, rain formation, and rain enhancement using the recent cloud seeding technologies (Kulkarni et al., 2012).

14. What has been done in different phases of CAIPEEX?

CAIPEEX has started in 2009 and have finished four phases of airborne observations

Phase I: Airborne observations of cloud microphysical parameters, aerosol size distribution, cloud condensation nuclei (CCN) concentrations and environmental parameters such as temperature, humidity and winds were carried out with the help of a twin engine Piper Cheyene pressurized aircraft in 2009 at Pune, Hyderabad, Pathankot, Bengaluru, Guwahati. This experiment was to survey the aerosol, CCN and cloud droplet characteristics over different parts of India and to identify a suitable location to conduct cloud seeding

Phase II: During the Phase II of CAIPEEX (during 2010-2011), airborne observations were conducted with Hyderabad as the base station with a seeder and a research aircraft. CAIPEEX 2011 an Integrated Ground Observational Campaign (IGOC) was conducted, in which ground to cloud layer observations were carried out in an integrated way, addressing the thermodynamical and microphysical aspects of convection over the lee side of Western Ghat.

Phase III: The Phase III 2014 of CAIPEEX started in May 2014 with a setup of ground based and airborne observations started on 9th Sept 2014. 49 Hours of airborne observations were conducted from Varanasi during the Phase III. Ground based observations were conducted from the rural campus of Banaras Hindu University. The Phase III also carried out several aerosol and precipitation chemistry measurements on board the aircraft In 2015, aircraft observations were carried out from Kolhapur in the triangular area between Kolhapur, Mahabaleswar and Solapur in the month of July 2015 for 75 hours. These observations of cloud microphysics, aerosol, black carbon, chemistry and GHG are conducted with specific emphasis to understand the cloud characteristics in view of the planning for randomized seeding experiments for 2018-19.

Phase IV:

The main goal of the observational campaign of Phase IV 2018-19 was to provide high quality observations of cloud and precipitation related processes in natural and seeded clouds over the rain shadow region. One of the main objectives of this experiment is to investigate suitable conditions under which cloud seeding works and experiment is conducted to document scientific evidence from microphysical changes in clouds to the rain development and eventual fall out to the surface.

As part of the experiment, physical and statistical evaluation of cloud seeding were carried out. The statistical approach uses a randomization procedure to collect samples. The physical experiment documents the changes in cloud before and after seeding and precipitation development in clouds. CAIPEEX Phase IV (2018 and 2019) experiment used hygroscopic seeding at the cloud base with calcium chloride flares. A few experiments with glaciogeneic seeding in deep convective clouds were also conducted. As part of the experiment,airborne observations were carried out from the bases Baramati, Aurangabad and from Solapur airport. High quality observations were collected in convective clouds and the range of instruments used in the experiment gives a complete size distribution of aerosol particles from nanometers to ice particles and raindrops of a few millimetres. The particulate chemistry measurement samples were also collected. These observations led to documentation of the policy report, which is available at https://www.tropmet.res.in/~lip/Publication/Technical-Reports/CAIPEEX-Report-July2023.pdf

15. How can we distinguish whether the rainfall is due to seeding or naturally?

The rainfall is formed by a complex process where there is a phase change of water in all three forms. There are clouds at different altitudes in the monsoon environment. In the complex system, isolated convective clouds are targeted with airborne seeding. A groundbased radar could be used to document the cloud properties and a ground-based rain gauge network could be used to record the rainfall. The concurrent use of both radar and rain gauge is a must for identifying the right cloud, tracking the cloud after seeding, and finding rainfall attributed. However, whether the rainfall received is due to seeding can be investigated by the cloud microstructure in detail with airborne observations and complemented by detailed numerical simulations. The present-day models can simulate cloud processes and the impact of seeding. The model can be validated with observations and then used for cloud seeding study.

16. Why do we prefer randomization in cloud seeding?

Clouds are able to rain naturally and when clouds are seeded, it is impossible to separate the natural and seeded precipitation.

Cloud seeding introduces a complex interaction within the cloud and every detail cannot be documented. Thus, to execute unbiased statistical analysis among seeded and un-seeded clouds, generally, cloud seeding experiments are randomized. It involves randomly selecting suitable clouds to seed and deciding not to seed, based on a randomization method, just like in any other discipline (for eg. in a medicine trial). This is done so that the effects of seeding can be compared with the natural variability of rainfall. This technique is similar to randomized clinical trials in the medical field.

The energy produced within the cloud is through latent heating as cloud droplets grow by condensation or ice particles grow by vapour deposition. The energy thus gained in the atmosphere will indeed change the dynamics of the cloud. There will be circulations within the cloud, which will redistribute cloud mass and also lead to cloud growth/dissipation. These cloud motions are small - big and sometimes can evaporate the cloud completely if the environment is dry and environmental air enters the cloud. The dry air will enter the cloud, and it will evaporate growing cloud droplets. This will either suppress the rainfall formation or make the cloud stay longer with small cloud droplets. Thus, every cloud in nature is different, and they have chaotic behavior due to the dynamics and therefore, the randomization technique is used in cloud seeding experiments.

17. Which type of seeding is favoured (Hygroscopic/Glaciogenic)?

There is no particular preference, it is totally based on the type of cloud and its suitability at a geographical location. Clouds have varied liquid water in them, and some clouds may have only ice in them. The glaciated clouds are not suitable for seeding. There has to be liquid water in the cloud for any type of seeding. In tropical environments, the deep cumulus clouds are usually very chaotic due to the strong vertical motions in them, and they exchange mass, energy and water vapour with the sub-cloud layer as well as the layers above.

18. How much seeding material is to be used during seeding per cloud? Can we control this quantity?

Typically 2-4 flares are used per seeding event of a single cloud. The flares contain several thousands of seed particles within a cubic centimeter of air.

19. What are the effects of the Overuse of seeding material on clouds?

Overseeding can evaporate the cloud as too many particles may share available water vapour in the atmosphere and the size of cloud particles thus formed may be too small to form any collisions and raindrops.

20. How to improve seeding material? How sure are we about the seeding material we are using nowadays?

The seed particles could be tested with several instruments available and can check their suitability for cloud formation.

Seed particles could be improved by studying the aerosol composition and their hygroscopicity and CCN activity (how the particles can form cloud droplets under increasing saturation above 100% as inside the cloud). These parameters are important to decide on the efficacy of the seed particles to form cloud droplets. These parameters depend on the particle size and the chemical composition/coating on the seed particles. For eg. Potassium iodide, sodium chloride, and calcium chloride have a natural affinity for water vapour (high hygroscopicity). The seed particles are supposed to be of higher hygroscopicity compared to the particles in the ambient air that will readily form cloud droplets. The size of particles has a crucial role as larger size particles will form cloud droplets easily due to a large surface area on them. Sea salt for e.g. is a good CCN due to its large size and hygroscopicity. It is important to understand the particle size and composition before choosing the seed particle.

The AgI pellets are traditionally used in glaciogenic seeding where the particles act as ice nucleation particles. Burning of AgI with acetone may make it more hygroscopic and could act as a hygroscopic seeding agent, first acting on shallow warm cloud layers (and may also act as ice nuclei). The introduction of these seeding particles is expected to increase the chances of rain formation through quick pathways such as collision coalescence or ice formation processes (such as deposition or rimming and rain or snow forming through the chains of microphysical processes).

21. Which is the best RADAR to identify clouds during seeding?

C-band radar is recommended for use in a cloud seeding project due to the range and resolution and lower attenuation than the X-band radars. The radars should be able to make quick scans to document the cloud evolution and precipitation. Often the precipitation forms within 15 min of seeding and that should be documented within the radar scan interval and clouds need to be traced during their lifetime, which can last for an hour or more.

22. Is glaciogenic seeding really effective, if yes why are we not using this all the time?

Clouds are segregated into two groups in terms of seeding: warm and cold clouds. Warm clouds exist where the cloud top is below freezing and only contain liquid drops. Cold clouds primarily exist where the cloud top temperature is above freezing level (having temperature <0^oC) and contains ice and liquid. **The liquid present in subzero temperature is called supercooled liquid. If a solid particle comes in contact with the supercooled liquid, it would spontaneously deposit on the surface of soild particle.**

There is documented evidence in the midlatitude orographically forced cloud systems that glaciogenic seeding enhances snowpack. Over the Indian region, especially over the rain shadow region in the peninsula, a number of factors are playing crucial roles in rainfall. We have mostly shallow convective clouds (warm clouds) or different layers of clouds with both warm and cold regions. In warm clouds, glaciogenic seeding is not recommended. Deep convective clouds are noted during the premonsoon and post monsoon season as the winds become low and the atmosphere is unstable. The clouds are vigorous and form cold regions and lead to thunderstorms. Typically, clouds are seeded during their developmental stages with adequate supercooled liquid in them. In cold clouds, glaciogenic seeding is found to increase ice crystals, as more supercooled liquid water deposits on the seeded aerosols; the so called ice nuclei particles. However, these ice crystals thus formed have to grow to larger sizes to start falling and as they cross the freezing level, they melt and make raindrops (which will happen only under suitable conditions in the upper atmosphere). If the environment is too dry, the clouds evaporate and may sometimes form virga, with rain not reaching the surface. Large-sized ice crystals will only fall out as 'snow' and melt to form raindrops that are reaching the ground. In colder climates, the freezing level is close to the surface or at sub zero temperatures, the snow falls to the surface. Glaciogenic seeding is used in the USA to enhance snow pack.

23. After seeding, the cloud rains, but sometimes rain does not reach the ground! Justify

Clouds do rain but do not reach the ground as a result of the environment being very dry and the droplets evaporating.

24. Practical difficulties during seeding?

One major aspect is that clouds grow rather rapidly and we need to target clouds in the early part of their growth before they start raining. The seeding in raining clouds will wash out seed particles into the boundary layer and will not serve the purpose. So, one needs to decide the correct time to intervene. The pilot needs to be well trained and knowledgeable about the way to seed near the cloud base in the updrafts and also be proactive in the requirements. There are several safety needs as flying in the upper-level clouds can lead to icing on the aircraft, which is hazardous. Several precautions need to be taken for the proper conduct of the experiment and a coordinated effort is needed. One should also know the correct details of weather conditions and any imminent severe weather, which may be of concern for safety. Another aviation safety concern is regarding birds.

25. How to tackle a lot of restrictions in flying during seeding in India?

There are several flying restrictions and a number of permissions need to be taken well in advance. One must understand that these are a requirement for safety and security. This must be followed with a good understanding and dialogue between stakeholders and authorities.

26. What type of infrastructure is needed in the future to get more success in seeding in India or any place?

It has been noted that information on clouds before, during, and after seeding is a requirement and ground-based radars can give unprecedented details of convection and its properties. A well-equipped aircraft with seeding and other observations (minimum on the cloud water and updrafts) for selecting the cloud for seeding. There is also a requirement for a rain gauge network to document the rainfall received at a location. The density of rain gauges can be a minimum of one gauge in every 25 x25 km^2 area as per CAIPEEX.

27. Is cloud seeding always done for rain enhancement? Is there any cloud seeding for rain suppression?

Cloud seeding is done for weather modification applications such as a) rain enhancement, b) reducing rainfall c) fog/pollution suppression, and d) hail suppression. These are all active areas of research in weather modification science.

28. Is it possible to dissipate dense fog using a cloud-seeding procedure?

There appears to be some effectiveness in using water droplets in such conditions for seeding in warm fog layers. But in ice fog, there are documented studies for fog dispersion.

29. What is the aerial coverage of cloud seeding?

Cloud seeding typically can be done with one aircraft in a 100 x 100 km^2 area. The clouds will move from the location of its intervention and could be monitored in the surveillance area of a C-band radar over nearly 200 km^2 downwind of the seeded location.

30. Can cloud seeding increase total rainfall over a large area or it just redistributes rainfall over a large area?

The amount of water vapour is fixed and the cloud seeding is indeed found to redistribute rainfall. With proper planning in locating the target area, and understanding the clouds and their diurnal variations, the seeded convection can redistribute rainfall to other rain sparse regions. One must remember that all seeded clouds do not make rainfall. Large area enhancement in rainfall is still a research area and is not proven. This is due to the large variability in the natural rainfall and the seeded rain cannot be separated, unless a randomization procedure is followed, detailed numerical studies and observations are used as supportive evidence as per WMO guideline.

31. Can cloud seeding be done over any type of landmass or is there any criterion to choose an area?

Cloud seeding can be done on any landmass, however, seedable clouds have to be available. Only certain regions will have seedable clouds and such locations have to be identified beforehand. Clouds of sufficient depth >1 km has to be present with adequate convection representing liquid water in the clouds before rain forms inside those clouds.

32. What is the lifetime of cloud seeding material after seeding?

The cloud-seeding material can be removed by deposition and wet scavenging, just like any other aerosol particles emitted into the atmosphere. It depends on the available environmental conditions.

33. Can cloud seeding lead to any natural hazard?

Cloud seeding occasionally is reported to have produced high rainfall. But seeding is not recommended in conditions of severe weather.

34. What are the alternate, cost-effective methods of seeding, instead of using an aircraft?

Seeding from a higher elevation, using drones or other methods such as guided balloons for seeding at the cloud base.

35. There is a common notion that seeding can cause rainfall even in the absence of clouds. Is this true?

No. Seeding requires suitable clouds. Not all clouds are seedable.

36. Seeding could result in better irrigation and hence changing land-use patterns. What could be the result of this?

Regional impacts would be assessed with long-period data, this is open for investigation.

37. Can cloud seeding experiments suppress hail in convective clouds during the pre-monsoon season?

There are a few experiments conducted around the world on Hail suppression (e.g. Argentina, Western Europe and USA). However, there is no statistical evidence and this topic is open for investigation and requires further research.

38. What are suitable locations in India where cloud seeding experiments can be conducted?

We require a regional analysis on this matter with proper information on the cloud properties and their diurnal variations. Seedable clouds are not available everywhere.

39. Is cloud seeding material safe for our environment?

Studies regarding the possible environmental impacts of seeding are very limited in the literature. Silver is toxic and if released in large amounts, is bad for the ecosystem and humans. AgI is an Insoluble substance used in Cloud seeding. The soluble form is toxic in high amounts, say 10 gm of silver nitrate (which was used in early days) consumed by a human is fatal and the safety limits vary for different organisms. The maximum amount which can dissolve in water is 1.6 parts per thousand million (a few micrograms of silver ions), in food (mushrooms) few hundred of micrograms are available. But even small amounts (0.2 micrograms) are highly toxic to fish, microorganisms, etc. (aquatic life). Cloud seeding may increase 2-50 times of Ag (that is up to 20 micrograms noted from observations). Iodine is 54% of the mass of AgI molecules and is not found to have toxicity levels. So far there are insufficient evidence in the literature that cloud seeding has contributed to an environmental impact. However, it is recommended that any cloud seeding program should evaluate environmental impacts.

40. Is there evidence for the efficacy of cloud seeding?

Glaciogenic seeding in orographic clouds is well documented now. Rauber et al., (2019) give a comprehensive and current state of glaciogenic seeding in orographic clouds over the western part of the USA. Orographically forced clouds have a natural lift over the terrain. The Windward side of the terrain gives convergence of moisture and forced lifting. The overall idea was to convert the liquid water present in the subzero temperatures (supercooled liquid water) in the clouds upstream of mountain ranges to increase snow precipitation by introducing more ice nuclei. That experiment is the most comprehensive one, illustrating the physical, statistical, and numerical modelling components used for addressing the underlying hypothesis. The experiment has implemented several state-ofthe-art instruments; however, the understanding of ice nucleation (through several mechanisms) remains elusive. The study has also indicated that advanced numerical models can be used for selecting seeding locations. There is documented evidence through physical evaluation of glaciogenic seeding that by seeding clouds containing supercooled liquid with AgI, precipitation can be traced from the cloud to the surface.

However, there is no documented physical evidence of hygroscopic seeding, especially in convective clouds which are more chaotic due to dominant dynamical interactions with the environment. The main caveat is that the cloud seeding signal may be several orders smaller than the natural variability and documenting the seeding effect is thus very challenging. As a result, following the chain of processes after seeding is essential to the precipitation at the surface. Often a hypothesis is formulated prior to the experiment about the chain of processes through which precipitation may develop in clouds due to seeding. This also includes tracking seeded plumes, finding out the interaction between seeded and unseeded clouds, and the extra-area effects, i.e. impact of seeding outside the target area. These aspects are studied with specially-suited model experiments supported by well-calibrated radar observations and rain gauges.

Ground-based seeding using Silver Iodide (AgI) and acetone burners was traditionally used in cloud seeding due to their ease of implementation. Often the ground-based AGI burners are not as effective as airborne methods in dispensing seeding material into clouds. When the seed material is dispensed from the ground, it may get suspended in the lower atmosphere and can get lost in the boundary layer, depending on the atmospheric conditions, and may not be suitable for conditions over the rain shadow region. The best option is to release the detectable concentration of seed material within the cloud.

41. Operational cloud seeding

Operational cloud seeding is practised in more than 56 countries worldwide (Flossman et al., 2019). There is also a large thrust on weather modification research for assessing various weather modification prospects. There is still uncertainty regarding the quantitative effects of cloud seeding to enhance precipitation (WMO World Meteorological Organization, 2018b: Plans and Guidance for Weather Modification Activities in Executive Council Annex 2 to Decision 53 (EC-69)). WMO recommends detailed research programs focussing on scientific documentation of cloud seeding effects and it is a topic in the WWRP current plan (WMO 2010). Research programs are ongoing in Australia, China, India, the Russian Federation, Thailand, the United Arab Emirates, and the United States of America. As per the WMO peer review report (2018), “toxicological, ecological, sociological, and legal issues, as well as extra-area effects, need to be considered” before any operational seeding program. (Extra area effects impact on precipitation outside of the seeded area of interest).

Typically orographic clouds (over mountainous areas with a natural lifting process) and convective clouds (having convective upward air motion) are selected for seeding. There is extensive scientific literature on glaciogenic seeding in orographic clouds (WMO 2018). These studies mainly come from the mid-western USA and the well-established research programs illustrate that glaciogenic seeding indeed can lead to a chain of processes leading to precipitation in the clouds (French et al., 2018). The clouds under orographically forced lifting are considered on the windward side of mountain ranges for seeding. These clouds from the Mid-western USA with supercooled liquid were targeted for cloud seeding to increase the snowpack.

Cloud seeding in orographic clouds has shown some promise for precipitation formation. Quantitative evaluation of such rain enhancement has recently become available. This is mainly due to the fact that precipitation due to seeding effects (if any) is not differentiated from natural precipitation. This fact introduces significant uncertainty in the outcome of cloud seeding. Consequently, WMO recommends that seeding evaluation be carried out with both a physical and statistical experiment and numerical simulations to document the impact on precipitation.

42. Why are convective clouds a challenge for cloud seeding?

Determination of cloud seeding efficacy in the convective clouds has been a challenge mainly due to the difficulty associated with the complex dynamics of these cloud systems. The seeding signature associated with the flare seeding in convective clouds could not be documented with conventional methods.

It may also be noted that not every type of cloud is seedable and the evaluation of cloud morphological and climatological characteristics is needed before operational seeding. The rapid transformation of convective clouds makes it even more difficult to target them at the right time. The type and location of seeding, cloud base height, cloud depth and liquid water content in the clouds, the diurnal cycle of precipitation, etc. are very important in decision making.

43. What is the international status of cloud seeding?

Weather modification is receiving more attention around the world. As many as 56 countries are involved in such activities for rainfall enhancement, fog suppression, pollution dispersion, weather management, etc. The current comprehensive state of precipitation enhancement science is depicted in Flossmann et al (2018, 2019) in the WMO peer review report by the WMO Expert Team on Weather Modification. The interaction between cloud dynamics and its microphysics is the most challenging topic in understanding the impact of seeding. The hydrodynamic changes within a cloud upon introduction of cloud seeding particles is envisioned as an aerosol-cloud-precipitation interaction, where more aerosol particles (cloud condensation nuclei) depending on their cloud activation properties may form cloud droplets or ice particles and grow by diffusion at different supersaturations as available.

There is 26 mm m^{-2} of water in each column of air with a cumulative amount of 13×10^3 km^3 of water vapour in the atmosphere. Not all water is removed from the atmosphere in the form of rain at the surface. The global warming scenario introduces the idea that dry places get drier and wet places get wetter. The need for freshwater resources is sought in various ways, including rain enhancement through cloud seeding (UN 2020).

44. What is the biggest challenge in cloud seeding?

The biggest challenge in rain enhancement is the difficulty in separating the natural and modified precipitation due to the significant natural variability (NRC, 2003), which is controlled by the non-linear processes and interaction of cloud microphysics and dynamics.

45. What are the recommendations?

The National Research Council (NRC, USA) has recommended a three-component approach to the problem a) physical experiment b) statistical experiment and c) numerical seeding experiment. It has been suggested that the sample size include a variety of environmental and background aerosol conditions akin to the target area and numerous cases are needed to document the repeatable nature of the outcome of seeding. Studies have also indicated the value of in situ measurements to document the physical chain of events in the precipitation process with advanced technology to probe clouds and advanced seeding models to follow and validate the precipitation formation processes. The direct measurements of precipitation through a network of observations of various kinds including the precipitation chemistry and tracers to track the seed material in precipitation have been recommended.

46. What is the seeding strategy?

There are a variety of seeding strategies identified, many depending on the target cloud type, of which wintertime orographic and summer convective clouds are most sought after. There is a rich literature on wintertime orographic seeding from the Mid-western United States where glaciogenic seeding is done operationally. In the SNOWIE project, attempts were made to address the problem with a three-component approach. On the basis of ground-based seeding, recent results from the Wyoming experiment indicate a 5% increase in precipitation due to seeding impact.

47. How research studies on glaciogenic seeding is conducted?

In the glaciogenic seeding, the examination of cloud microphysical processes following the airborne application of AgI as ice nuclei is conducted. The estimation of the efficacy of seeding from the Idaho (SNOWIE) experiment (on Winter orographic clouds) is based on observations with detailed instrumentation on the aircraft and ground-based remote sensing instruments.

48. What is the major challenge in proving cloud seeding efficacy?

The detection and quantification of precipitation due to seeding is almost impossible to isolate from the natural variability in the precipitation. The seeding signature in the precipitation will be a very small signal in the large variability of natural precipitation. This is the most intrinsic problem with assessing the efficacy of cloud seeding implementation.

49. What has changed recently in technology?

The new and improved instrumentation to observe the three-dimensional structure and evolution of clouds, and better numerical modelling capabilities have offered the capability to evaluate the potential of cloud seeding for precipitation enhancement.

50. What can be suggested for the environmental assessment?

The snow or precipitation at the target site has to be analyzed for the presence of silver and other minerals. The seed particle dispersion, transportation, and deposition need to be understood based on the conditions over the target area. In several instances, tracers are used along with seeding agents. Ground-based seeding has contributed to the detection of a higher tracer of seed particles at the surface than in airborne seeding.

51. What are the advances in recent years?

Remote and in situ observational tools, Polarimetric radars, Doppler lidar and airborne radars, Cell-tracking software such as Thunderstorm Identification, Track-ing, Analysis, and Nowcasting; Dixon and Weiner 1993 (TITAN), Microwave radiometer, Airborne instrumentation, cloud condensation nuclei and ice-nucleating particle observations, Cloud and precipitation physics modelling involving seeding effects, Advanced targeting and evaluation tools (Models for plume tracking, seeding effects, etc.) all provide more understanding on the seeded clouds and associated precipitation.

52. The Chronology of events in the weather modification around the world

1940:

- Dry ice into supercooled liquid cloud cause glaciation (Schaefer 1946)
- Silver iodide (AgI), glaciated supercooled clouds (Vonnegut 1947)
- National Academy of Sciences reports, WMO reports, and more.
- Special Commission on Weather Modification (1966)
- Statistical analyses using target and control approaches were flawed (Rangno 1979)

1970:

- Airborne optical array probes and use of radars (polarization) advancing
- Indian cloud physics studies and cloud seeding experiments by IITM

1980-90s:

- (After the report by Kerr 1982), no funding for cloud seeding research
- Orographic cloud systems in Wyoming and Idaho, Rainfall enhancement research from convective storms from South Africa and Thailand (Silverman 2001a, 2003)

- Chinese hail suppression experiment in 1980. Currently, the Beijing Weather Modification Office, China is believed to be the world's largest with 37,000 people nationwide working on the cloud seeding aspect

- 11 year cloud seeding by IITM (Murty et al., 2000)

2003:

- NAC Report: Potential application of new technology for evaluating cloud seeding
- Physical evaluations for cloud structure with aircraft and radar and to model these clouds

2008:

- Beijing Summer Olympic rain suppression program

- CAIPEEX Phase I 2009, CAIPEEX Phase II (2010-2011)

2015:

- Significant advances (radars of different types, radiometers, airborne probes) in observing technologies and modeling capabilities (Geerts et al. 2015)
- CAIPEEX Phase III (2014-15) pilot experiment

2016:

- 56 countries had active weather modification operations (Bruintjes 2016, WMO).

2018:

- WMO Peer review Report 2018: Physical chain of events demonstrated the need for further research on ice and mixed-phase clouds. More research studies are recommended.
- 36 active weather modification programs in the USA. About half of the projects operate in summer and the other half in winter. Projects are funded by the state government, local government, private sector, and insurance companies. Some projects incorporate a research component.

2019:

- Several programs exist: The Wintertime cloud seeding to increase snowpack reservoirs, Hail-suppression operations in North Dakota, Rain enhancement from convective storms in Texas, Orographic clouds for the Snowy Mountains of Australia (Manton and Warren 2011), CAIPEEX (Since 2009),

2020:

- Documented evidence on snow enhancement on the ground from SNOWIE for glaciogenic seeding

2021:

- Documented evidence for convective cloud hygroscopic seeding from CAIPEEX using randomization experiment
- Seed particle tracking in the cloud

53. What are the basic components required for cloud seeding?

Aerial cloud seeding and ground-based cloud seeding have different requirements

Airborne seeding

Aerial cloud seeding can be done with a cloud seeding aircraft that can seed clouds by burning the flare at a greater altitude from the surface. This requirement comes when the cloud base is at an elevated height or seeding has to be done from the top of the cloud.

Cloud seeding aircraft will be a modified aircraft that will have flare racks attached beneath both wings and there will be triggering electronic circuits inside the plane. Pilots will ignite the flares with the electronic switch.

The minimum Specifications of the seeder aircraft can be the following:

Parameter	**Specification (at maximum gross weight)**
Minimum lowest operating altitude	500-1000 ft AMSL
Minimum highest operating altitude	25000 to 28000 ft AMSL with full load and full fuel (Note: The aircraft should be able to do the cloud top seeding)
Sampling Speed	60-120 m/s
Ascent rate	400 – 500 ft /min
Endurance	4 – 5 hours
Range	2000 km minimum
Special requirements	Air inlets (isokinetic inlet and reverse flow inlet) instrument racks
Instruments	Certification for listed instrument inlets and related modifications
Research power	> 5kW at 28VDC > 2kW at 220VAC 60Hz > 1kW at 115VAC 60Hz

A series of permissions for importing and operating the aircraft etc. are needed. The set of permissions is from various authorities such as DGCA, AAI, DRI, MHA, Customs, Ministry of Defense, Regional and local airport authorities, local law enforcement, etc.

Glossary

Aerosol: Suspended particles in the atmosphere, composed of either solid or liquid particles

Aggregation: The process by which ice crystals stick together and grow in size and mass

Burn-in-place flare: Cloud seeding Flare that is fitted on the wing of the aircraft and ignited with a short circuit.

Cloud droplet: Water drops having a size in the range of 2-50 micrometer and suspended in the air. An aggregation of cloud droplets forms the cloud.

Cloud condensation nuclei (CCN): Aerosol particles that have an affinity for water vapour and can form cloud droplets under supersaturated conditions

Cloud seeding Flare: Compressed cloud seeding material which is burnt to produce smoke containing numerous CCN

Cloud base: Height above the MSL where clouds start forming due to condensation of water vapour in the atmosphere on the aerosol particles

Cloud depth: Difference between the cloud top and cloud base heights

Cloud seeding: The use of additional known and well-characterized aerosols, other than those present in the atmosphere, that can form different-sized cloud droplets with the intention to influence the process of raindrop formation

Collision coalescence: Primary process, affected mainly by the turbulent flow inside a cloud, through which warm rain formation occurs. The seemingly chaotic movement of fine cloud droplets makes them collide and coalesce to form bigger droplets. The large enough (having size >24 micrometers) cloud droplets feel the force of gravity and fall through the cloud. During this fall, they collide with other small droplets and become even larger in size finally leading to the formation of raindrops

Dendrites: Pristine ice particles in the cloud that grow on the ice nucleating particles (CCN for ice formation) by depositing water vapour in the atmosphere. These are formed in the region where the ambient temperature is between -12 to -16^{o}C

Evaluation site: Region where cloud seeding evaluation is carried out by checking the natural rainfall

Ejectable flare: Flares that are dropped from the aircraft's fuselage into a growing cloud

Glaciogenic seeding: Introducing ice-forming particles (CCN for ice formation) in the cold region of the clouds. This is usually carried out at the top of the cloud having a sufficient liquid water content

Glaciation of a cloud: The process of formation of complete ice particles without any liquid water left over. This process forms ice clouds

Mixed-phase clouds: Clouds with the presence of both cloud water and ice

Hygroscopic seeding: Introducing cloud seeding particles that could lead to the formation of water drops. These are usually dispersed at the base of the cloud, but sometimes may as well be introduced inside the cloud under certain conditions

H-M Process: Hallet-Mossop process in clouds occurs in the temperature range -3 to -10 ^{o}C where the spontaneous breakup of freezing liquid drops and the resulting splintering leads to the production of many ice crystals. This is a commonly observed process in the monsoon clouds

Ice nuclei particle (INP): Ice-forming particles in the atmosphere

Numerical simulations: Mathematical equations describing the atmospheric state, cloud development, and rain formation are solved with the help of a computer. This numerical experiment may be used to study the impact of cloud seeding over a region of interest

Physical experiment: The impact of cloud seeding is checked physically with sophisticated instruments to register the growth of cloud droplets and the formation of raindrops

Polarimetric radar: A dual-polarised C-band Doppler radar that can measure the geometric (shape, size, etc.) and mechanical (displacement, velocity, etc.) properties of the rain and ice particles in a cloud

Randomization experiment: The clouds are seeded in a random manner following standard randomization procedures. Rainfall from the seeded and unseeded clouds are compared for statistical tests

Raindrop: Water drops with sizes from 1- 6 mm. These are formed by the melting of ice or the collision coalescence of cloud drops

Secondary ice production: The formation of ice particles in the cloud via indirect processes other than the ice nucleation process

Supercooled water: The condensed water in the sub-zero region of the cloud

Target site: The region where cloud seeding is done for rain enhancement

Vertical velocity: Vertical velocity at a location, typically within the cloud or in the atmosphere, in general. A stream of air with upward (downward) vertical velocity is called an updraft (downdraft).

Warm cloud layer: The layer of cloud wherein the temperature is above 0^{o}C.

Further Reading:

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