Ministry of Earth Sciences
Government of India

Cloud Aerosol Interaction and Precipitation Enhancement Experiment

CAIPEEX

Cloud seeding experiment

Results and Recommendations

Ministry of Earth Sciences (MoES)

Indian Institute of Tropical Meteorology (IITM)

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Clouds during CAIPEEX IV over Solapur

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EXECUTIVE SUMMARY

Availability of fresh water in semi-arid and arid regions of India is a major challenge, especially in times of deficient rainfall. Moreover, the rapid rate of groundwater depletion in several areas of India poses an additional constraint on water availability. Local bodies and governmental agencies seek alternate and viable solutions for enhancing water availability. To address the impending need for water availability, several state governments (including Karnataka, Maharashtra, and Andhra Pradesh) have expressed interest in adopting innovative strategies such as cloud seeding to enhance rainfall and manage drought.

Cloud seeding is considered an effective technique for weather modification, especially to enhance rainfall in rain shadow areas which can boost agriculture and the economy. It has been implemented by several countries of the world[1], including the USA, Australia, UAE, and China, and seems to hold the potential to mitigate the looming crisis of water scarcity and inadequate rainfall in several parts of our country. To execute cloud seeding in India, a scientific basis for enhancing rainfall over a selected region or geography is required. For a cloud seeding project to be successful, well-tested protocols specifically designed for a region must be developed. As of today, technological advances in instrumentation, equipment, and seeding methods have made it possible to evaluate the viability of cloud seeding and develop protocols to accomplish relative enhancement [(seed-no-seed)/no-seed] of rainfall in a given region. The Indian Institute of Tropical Meteorology (IITM), Pune, an autonomous institute under the Ministry of Earth Sciences (MoES), Govt of India, has conducted in-depth investigations to test the feasibility and effectiveness of cloud seeding, as part of Cloud Aerosol Interaction and Rainfall Enhancement Experiment (CAIPEEX) Phase IV, at Solapur, Maharashtra. The outcome from this experiment shows that cloud seeding is an effective strategy for enhancing rainfall in a region under suitable conditions. The characteristics of suitable clouds that can be targeted to enhance rainfall have been identified. Moreover, elaborate protocols and guidelines have been developed for policymakers and stakeholders to plan and conduct cloud seeding in India.

CAIPEEX IV has shown that rainfall can be enhanced by up to ≅ 46±13 percent at some locations and on average, ≅ 18±2.6 percent in 100 square kilometers (km^2) area in the downwind of seeding location over the rain shadow region of Solapur, Maharashtra. The hygroscopic cloud seeding methodology was used, amounting to an increased rainfall and contributed to ≅ 867 million liters of water, yielding a positive cost-benefit ratio.

Over two years (2017-19), scientists at IITM evaluated 276 clouds to test the effectiveness of cloud seeding. The cloud seeding was conducted with aircraft. All measurements were done using a wide network of state-of-the-art equipment such as automatic rain gauges (ARGs), radars, radiometers, and aircraft. The results show robust statistical significance above the 95 % confidence level. A high-resolution numerical model was also developed to help stakeholders to identify target locations, seedable clouds, and the suitable seeding strategy to enhance rainfall in an area.

MINISTRY OF EARTH SCIENCES

The Ministry of Earth Sciences (MoES), Government of India, is mandated to provide services for weather, climate, ocean and coastal state, hydrology, seismology, and natural hazards; to explore and harness marine living and non-living resources in a sustainable manner and to explore the three poles of the Earth (the Arctic, Antarctic, and the Himalayas).

MoES was formerly the Department of Ocean Development (DOD), which was created in July 1981 as a part of the Cabinet Secretariat directly under the charge of the Prime Minister of India. It came into existence as a separate department in March 1982. The erstwhile DOD functioned as a nodal institution for organizing, coordinating, and promoting ocean development activities in the country. The Government of India notified DOD as the Ministry of Ocean Development in February 2006. In July 2006, the Ministry of Ocean Development was reorganized by the Government of India vide Presidential notification into the new Ministry of Earth Sciences (MoES).

The MoES is headquartered in New Delhi and comprises a network of ten institutes (two sub-ordinate offices, three attached offices, and five autonomous organizations) spread across the country. The sub-ordinate offices are India Meteorological Department, Delhi, and National Centre for Medium-Range Weather Forecasting, Noida. The attached offices are National Centre for Seismology, Delhi; the Centre for Marine Living Resources and Ecology, Kochi; and National Centre for Coastal Research, Chennai. The autonomous organizations are the Indian Institute of Tropical Meteorology, Pune; Indian National Centre for Ocean Information Services, Hyderabad; National Centre for Ocean and Polar Research, Goa; National Centre for Earth Science Studies, Thiruvananthapuram; and National Institute of Ocean Technology, Chennai.

INDIAN INSTITUTE OF TROPICAL METEOROLOGY (IITM), PUNE

IITM is one of the premier research institutes under the MoES, conducting research studies on monsoons, clouds, and climate. IITM was founded in 1962 and worked under the Ministry of Tourism and Civil Aviation until 1984. After operating under the aegis of the Department of Science and Technology, Ministry of Science and Technology from 1985, it was put under the MoES vide Presidential order with effect from 12 July 2006. Since then, IITM is the nodal institute in India for expanding research in the tropical Indian Ocean with special reference to monsoon meteorology and air-sea interaction of South Asian climate.

Picture: Landscape of the IITM, Pune, an autonomous institute under the MoES, Govt. of India

The observational programs at IITM have been providing useful and robust data on tropical clouds. Since its inception, IITM has been working on various aspects of weather modification, especially cloud seeding, to increase rainfall in the rain-deficit areas of the country by studying the properties and efficacy of clouds.

CAIPEEX

CAIPEEX is the acronym for Cloud Aerosol Interaction and Rainfall Enhancement Experiment, an important scientific field campaign conducted by the IITM, Pune, under the Ministry of Earth Sciences, Government of India. CAIPEEX aims to understand the possibility of enhancing rainfall in an area through cloud seeding. To know whether it can enhance rainfall in an area by cloud seeding, scientists require validated scientific data acquired through randomization, physical experiments, and numerical simulations as per the guidelines of the World Meteorological Organisation[1-3]. CAIPEEX has helped scientists to document cloud and rainfall processes and derive protocols for enhancing rainfall in a region.

CAIPEEX[5-13] began in 2009 (phase I), followed by 2010-11 (phase II), 2014-15 (phase III), and 2017-19 (phase IV). The first three phases of CAIPEEX comprised of research and studies on clouds and airborne observations of clouds and rain. The outcomes from the first three phases of CAIPEEX helped scientists at IITM to design cloud seeding experiments for CAIPEEX phase IV (Figure 1).

Figure 1: CAIPEEX IV aerosol and cloud observational facility at Savitribai Phule Shikshan Prasarak Mandal's N B Navale Sinhgad College of Engineering, Solapur, Maharashtra (top-left), two aircraft (top-right) and ground-based equipment such as radar and wind profiler (below) used for the experiment.

The results obtained through CAIPEEX IV have shed light on the following aspects:

- Protocols for identifying and targeting clouds suitable for seeding
- Cloud seeding signature in warm and cold clouds
- Randomized seeding experiments in warm clouds
- Robust statistical signature of enhanced rainfall due to seeding
- Evidence of redistribution of rainfall due to cloud seeding
- Evaluation of cold cloud seeding
- Decision support for seeding with numerical cloud models
- Evaluation of seeding hypothesis from observations and models

CLOUD SEEDING

Cloud seeding is a technique by which cloud-forming particles are used to increase rainfall. Cloud seeding is practiced in more than 56 countries worldwide including Australia, China, Russia, Thailand, UAE, and the USA, with a thrust on weather modification such as enhancing rainfall. Cloud seeding is of two types—hygroscopic and glaciogenic. Differences between hygroscopic and glaciogenic cloud seeding are elaborated in Table I.

The hygroscopic seeding is done at the base of warm clouds using seed particles with an affinity for water vapor. The glaciogenic seeding is carried out in cold clouds by seeding near the cloud top using Silver Iodide particles, which may form ice particles in clouds.

Hygroscopic seeding was attempted in the 1970s by IITM in India. It showed promising results but the statistical robustness was still inconclusive as far as relative enhancement of rainfall was concerned[4]. This is because results in cloud seeding experiments are known to have large uncertainty, which is particularly the case with the hygroscopic seeding method due to a lack of observational evidence and the complexity of convective clouds.

The underlying issue in knowing the feasibility of cloud seeding is that natural and seeded rainfall cannot be distinguished without a scientific evaluation. To address this issue, the IITM has established an observational facility at Savitribai Phule Shikshan Prasarak Mandal's N B Navale Sinhgad College of Engineering, Solapur, and at Shri Tulja Bhavani College of

Engineering, Tuljapur, Maharashtra, for long-term observations of clouds and rainfall over the rain shadow region of Solapur. A C-band radar is established to monitor cloud and rainfall properties. Two aircraft were hired for airborne cloud seeding and conducting in situ observations in clouds. Over a period of two years (2018-2019), CAIPEEX IV has tested the feasibility of both hygroscopic and glaciogenic cloud seeding methods to enhance rainfall in Solapur, which is a perennial water-deficit rain-shadow area in Maharashtra, India.

With well-controlled experimentation with a scientific basis and robust statistical analysis, CAIPEEX IV has found that hygroscopic cloud seeding enhances rainfall in a rain shadow area spanning 100 square kilometers (km^{-2}) in Solapur. Therefore, hygroscopic cloud seeding can be a useful and effective strategy to enhance rainfall in rain shadow or arid regions if clouds are chosen suitably in selected regions. Scientists have developed protocols and guidelines for stakeholders and policymakers to execute successful cloud-seeding projects.

Table I: Types of cloud seeding

	HYGROSCOPIC SEEDING	GLACIOGENIC SEEDING
Background	This seeding is done in warm convective clouds with a cloud base height of >0^{o} Celsius. It uses hygroscopic flares (e.g., Calcium Chloride ($CaCl_2$) particles) released at the convective cloud base.	This seeding is done in cold clouds having both ice and water. It uses ice-nucleating silver iodide (AgI) particles inside clouds to enhance ice particle production and increase rain from the cold part of the cloud.

Suitability	Hygroscopic seeding is suitable for the base of warm clouds with vertical velocity >1.5 m s^{-1} and liquid water content >0.5 g m^{-3}, without rainfall. A warm cloud depth of one kilometers or more during seeding. Relative humidity in the 2-6 km layer should be > 60 %.	Glaciogenic seeding is suitable in the deep cumulus and tropospheric stratus clouds over a region, where water drops are present below 0 ^{o}C. Supercooled liquid water content >0.05 g m^{-3} and cloud top vertical motions are present.
Flares	Four flares are burnt at the cloud base containing Calcium Chloride ($CaCl_2$), encased in 12 cm long and 7 cm wide tubes, which produce a large concentration of $CaCl_2$ aerosols near the cloud base. These particles have a high capability to form cloud droplets.	One flare per cloud is burned at the cloud top containing silver iodide (AgI) particles encased in thin tubes released within stratiform clouds or ejected inside convective clouds.
Photograph of flares		
Seed	The seed particles containing $CaCl_2$ are released by burning flares by the aircraft directly at the cloud base.	The ejectable flares containing AgI are dropped from the cloud tops by aircraft.

CONDUCTING CLOUD SEEDING

A suitable location with seedable clouds is chosen for a cloud seeding project, using data on cloud properties collected by radars and numerical models. A seeder aircraft is flown to the seedable target area. The aircraft is equipped with cloud-seeding flares that can produce seed particles. When the aircraft reaches the target area, cloud properties are investigated by the aircraft. If found suitable (see Table 1), the cloud seeding flares are burned near the cloud base where there is upward air motion, which takes seed particles into the cloud.

Seed particles aid the water molecules present in the cloud to condense around them rapidly. Large cloud drops are formed when small and large drops collide and coalesce, resulting in rainfall. A radar placed on the ground monitors clouds before, during, and after seeding experiments. Automatic rain gauges record the amount of rainfall received on the ground.

To distinguish between rainfall due to natural causes and cloud seeding, seeding experiments are conducted in a double-blind and randomized manner. Rain gauges are placed at different locations in the target area (see Figure 2). The randomized seeding experiment was conducted in 278 convective clouds, selected based on the criteria mentioned in Table 1. In this sample, 152 seed and 126 no-seed clouds were present. A comparison of rainfall from seed versus no-seed clouds sheds light on the effect of cloud seeding on the relative enhancement of rainfall.

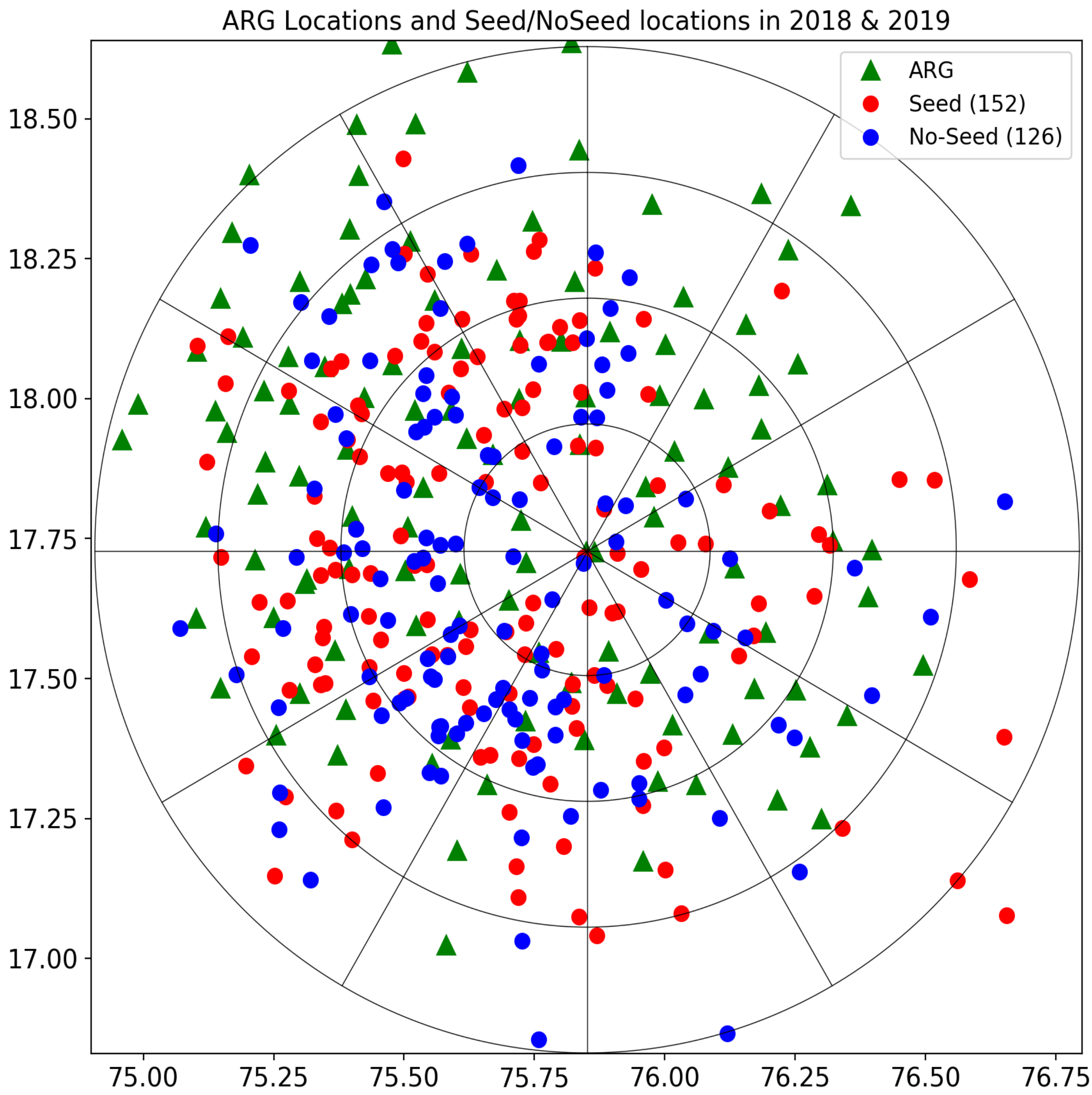


Figure 2: Locations (by latitude and longitude) of automatic rain gauges (green triangles) and the randomized seed/no-seed locations (red and blue dots, respectively) in CAIPEEX IV. The rainfall after cloud seeding was measured through a network of 120 automatic rain gauges placed on the ground spread across 100 square kilometers around Solapur, Maharashtra.

Table II: CAIPEEX cloud seeding experiment followed WMO[1-3] Standards

1	2	3
Setting parameters and identifying target clouds for cloud seeding	**Randomization of clouds into a seed/no-seed group**	**The outcome of observations and analysis**
▪ Cloud properties were recorded 5289 times with aircraft over the rain shadow region of Solapur between 2018-2019. ▪ 278 clouds that satisfied the criteria for hygroscopic seeding were chosen for cloud seeding. ▪ 62 (31 seed and 31 no-seed) clouds were chosen for glaciogenic cloud seeding evaluation. ▪ Several numerical cloud seeding experiments are conducted with sophisticated cloud models	▪ The clouds for the hygroscopic seeding experiment were randomized into a seed or no-seed group based on the experiment protocol. ▪ The aircraft was flown to the cloud base to burn four flares and dispense the seed material. Each flare took ≅4 minutes to burn completely. ▪ For a 'seed' cloud, the aircraft burnt the flares. For the 'no-seed' cloud, aircraft were flown in the same manner as if the decision were for seeding, to provide accurate controls for the experiment. The randomization strategy is summarised in Figure 3. ▪ In the glaciogenic seeding experiment, cloud properties of seed and no-seed categories are compared. ▪ Evaluated cloud models give the flexibility to test the different hypotheses of seeding to check complex processes inside clouds.	▪ Ground-based radar monitored the cloud properties before, during, and after the seeding. ▪ Automatic rain gauges recorded the rainfall on the ground. ▪ Data analysis was carried out using well-established statistical tools. ▪ Hygroscopic seeding resulted in a relative enhancement of rainfall ≅46±13 percent in isolated convective clouds, as per data from rain gauges downwind of the seeded location. ▪ The relative enhancement of rainfall over 100 square kilometers area downwind of the seeding location is ≅18±2.6 percent as per the radar derived rainfall data. ▪ Glaciogenic seeding did not cause significantly different rainfall between seeded and no-seed clouds at the seeding location. However, rainfall relative enhancement seen downwind of the seeded area, supported by the synoptic weather conditions.

Radar	Aircraft	Action
seed	no	no-seed
seed	yes	seed
no-seed	yes	no-seed
no-seed	no	seed

Figure 3: The selection of cloud for seeding is based on the protocol set in the experiment (Table I). The actual decision to seed the cloud is based on the randomization table above. Randomization procedure used in the CAIPEEX cloud seeding experiment. Before the campaign, two sets of sealed decision envelopes with the yes/no (for aircraft) or seed/no-seed (for radar) remarks were prepared by a group that was not involved in the campaign. If the action is to “seed”, two flares are burned on each aircraft wing.

Photo: Image of a raining cloud during CAIPEEX IV. The aircraft was used for seeding the cloud; its wing can be seen in the lower right corner of the picture.

RESULTS | HYGROSCOPIC CLOUD SEEDING EXPERIMENT

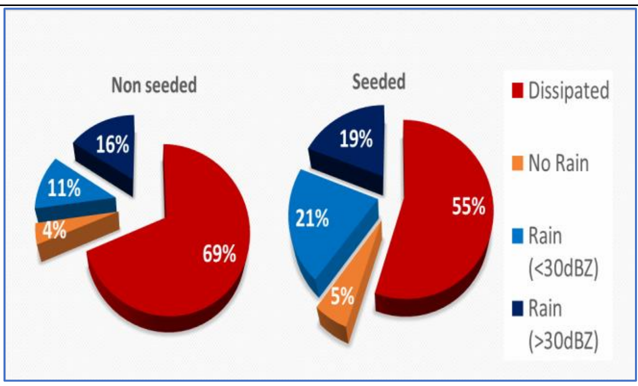
Table III: Results of randomized hygroscopic seeding	
Details of experiment	**Outcomes and inference**
▪ Over a period of two years (2018-19), 278 clouds were identified as suitable targets for cloud seeding experiments. ▪ The identified 278 clouds were randomized using a double-blind procedure into a seed or no-seed group. ▪ Of the 278 randomized clouds, 276 convective clouds are evaluated based on the data availability. It was found after the experimentation that 151 (54.7%) clouds turned out to be in the 'seed' category and 125 (45.3%) in the 'no-seed' category. ▪ Out of the 151 seeded clouds, 83 clouds (55%) dissipated and made no rainfall as isolated clouds. ▪ Out of the 125 no-seeded clouds, 86 (68.8%) dissipated and made no rainfall as isolated clouds. ▪ Out of the 151 'seed' category clouds, 60 (39.73%) clouds gave rainfall. Out of 125 'no-seed' category clouds, 34 (27.2%) clouds gave rainfall. The remaining clouds in each category neither rained nor dissipated. ▪ A summary of the findings is provided in Figure 4.	▪ As per rain gauges situated downwind of the seed location, there was a relative enhancement of rainfall by ≅46±13 percent in the 'seed' category clouds concerning the 'no seed' category clouds. ▪ As per radar observations over an area spanning 100 km^2 downwind of the seed location, there was a relative enhancement of rainfall by ≅18±2.6 percent in the 'seed' category clouds concerning the 'no seed' category clouds. ▪ These results are robust with statistical significance above the 95% confidence level. ▪ Clouds seeded at the early stage of their development resulted in enhanced rainfall. ▪ Clouds seeded at the early stage of their development also lasted longer. ▪ Extra area effects (impact on rainfall in places other than the seeded location) of seeding are observed and documented.
	

Figure 4: Summary of results of the hygroscopic cloud seeding experiment under CAIPEEX IV at Solapur, Maharashtra. (dBZ indicates radar reflectivity (a measure of raindrop size and thus rainfall) at the time of seeding) (left) and hygroscopic seeding caused cloud growth in selected clouds after cloud seeding resulting in relative rainfall enhancement.

Table IV: Results of the glaciogenic seeding experiment	
Details of experiment	**Outcomes and inference**
▪ Glaciogenic seeding experiment was a physical experiment, where randomization was not exercised. ▪ Over a period of two years (2018-19), 62 clouds were identified as suitable targets for glaciogenic cloud seeding experiments. ▪ Suitability of clouds was based on the availability of supercooled cloud liquid water content above 0.05 gram per cubic meter of cloud volume (g m^{-3}). Cloud tops with upward motions were chosen as targets. ▪ 31 suitable clouds were seeded with glaciogenic flares. ▪ 31 natural clouds with similar properties were identified, but they were not seeded. ▪ Both seeded and non-seeded clouds were observed with radar and the resulting rainfall was compared for seeding evaluation. ▪ The measurements were made using automatic rain gauges (ARGs), radars, and cloud and rain probing instruments on the aircraft as well as satellite observations.	▪ At the seeded location, there was no significant difference in the rainfall between the two cloud groups when the clouds were seeded using the glaciogenic cloud seeding method. ▪ All 31 seeded clouds rained spontaneously on the spot and also caused some increase in rainfall in the downwind area due to the atmospheric dynamics. ▪ All 31 unseeded clouds also rained on the spot. However, downwind areas received less rainfall compared to seeded clouds. ▪ The immediate rainfall in both seed and no-seed clouds occurred by the sudden melting of ice particles in the cloud. ▪ Besides the seeding impact, the relative enhancement in rainfall in the seeded clouds could also be attributed to the supporting synoptic weather conditions prevalent over the region. Differences in these effects could not be discerned. ▪ Further investigations are needed to affirm the effect of glaciogenic seeding in deep convective clouds.

CAIPEEX IV has developed a cloud seeding protocol for hygroscopic seeding of warm convective clouds, well-suited for the Indian scenario that can be used to enhance rainfall in a location based on validated scientific data and principles. This cloud seeding protocol is elaborated in Table V. Four stage operational plan is given in Annexure C for assessment, planning, operations, and evaluations.

Any cloud seeding program should take into consideration the following:

a) the infrastructure requirement
b) the site selection for seeding
c) the presence of clouds suitable for seeding at the site
d) a decision for seeding based on radar and aircraft observational facilities
e) execution of seeding at the appropriate time with aircraft
f) above (c-e) points should be well documented through proper observations
g) knowledge about the impact on the environment and ‘extra-area’ effects
h) economic impact assessment

With these basic requirements, the protocol mentioned below (Table V) may be considered for designing cloud seeding operations for the management of water scarcity at the catchment scale projects.

Table V Details on Facilities and Protocols for cloud seeding

S	Parameter	Selection criteria for executing a successful cloud seeding exercise to enhance rainfall
1	Infrastructure and project setup	▪ Cloud seeding projects require an upfront investment for setting up radar, a network of automatic rain gauges, and equipment for decision support systems that have a lifetime of up to 15 years if maintained properly. ▪ Aircraft with seeding and cloud tracking modalities will be the requirement for seeding, monitoring, and documentation. ▪ The detailed infrastructure requirements for a typical cloud seeding project are provided in Annexure A.
2	Site selection	▪ Catchment scale areas with seedable clouds (suitability as per Table I) should be chosen for cloud seeding projects. ▪ The first step is to document the natural variability of rainfall from long-term observations. ▪ Areas with severe weather events should be avoided for seeding intervention. ▪ It is advantageous to choose areas where there is natural cloud forming and lifting mechanisms such as mountains, convergence lines, etc. ▪ Numerical cloud models should be used to determine the operational area for cloud seeding projects, based on the seeding criterion/a decision support system on a case-by-case basis.
3	Time of seeding	▪ The suitable time window for seeding in Solapur was between 1230 PM-1530 PM. This time window for cloud seeding must be determined from observations for each site, based on the growing stage of clouds. This can be based on the properties of natural clouds and rainfall. Long-term radar, satellite observations, and numerical models can be used. ▪ Aircraft seeding operations should be planned two hours before the peak in the diurnal cycle of rainfall.

S	Parameter	Selection criteria for executing a successful cloud seeding exercise to enhance rainfall
		▪ High spatial resolution numerical cloud models can be used to determine the viability of cloud seeding for the season and find seedable locations.
4	Target/seedable clouds	▪ Warm base convective, developing clouds, preferably isolated, with warm cloud depths greater than 1 km, radar reflectivity factor <30 dBZ, cloud vertical motion >1.5 ms^{-1} at 300 m above cloud base, cloud water content >0.5 gm^{-3}, a well-defined cloud base with no rain falling out of the cloud base can be targeted. ▪ Environment should have high integrated water vapour content (> 5 cm), moderate values of convective available potential energy, cloud base height, and Cloud Condensation Nuclei. Relative humidity in a 2-6 km layer of >60 % favoring deep cloud growth.
5	Cloud seeding methodology	▪ During monsoon season, hygroscopic cloud seeding method (with cloud base seeding) is more advantageous in enhancing rainfall and longevity of clouds. Hygroscopic cloud seeding may be preferred over the glaciogenic cloud seeding method during the monsoon season, where the boundary layer is moist. ▪ Airborne seeding should be used for precisely dispensing seed particles, by flying at the cloud base and dispensing particles in the updrafts (vertical motions).
6	Cloud seeding steps	▪ The seeding mission and target area can be determined with the help of numerical model forecasts and radar observations. ▪ Aircraft should be flown to the base of the target cloud, as guided by the radar. ▪ Aircraft should check conditions as per Table 1 for seeding by making cloud penetration at 300 m above the cloud base. ▪ If found suitable, four flares containing Calcium Chloride particles or other tested hygroscopic seed particles may be

S	Parameter	Selection criteria for executing a successful cloud seeding exercise to enhance rainfall
		burned in order to release seed particles at the base of the target cloud.
7	Documentation of seeding impact	▪ The cloud seeding project should include a strong research component to monitor weather conditions before, during, and after the cloud seeding exercise. ▪ There should also be a strong decision support system for planning, implementation, and evaluation.
8	Assessment of economic benefit	▪ The cloud seeding project should include an assessment of economic gain derived from the cloud seeding project. ▪ The method of estimating economic gains of the CAIPEEX IV for Solapur is provided in Annexure B.
9	Assessment of environmental, extra area effects, and other/societal impacts	▪ The cloud seeding project should include a well-designed plan for investigating the environment, extra area (the impact on rainfall outside of the seeding area), and other societal impacts. ▪ In CAIPEEX IV, hygroscopic seed particles and the binding agents of seed material were traced in the cloud residue of seeded clouds and were only found within clouds. However, a detailed environmental assessment was not attempted in CAIPEEX IV. ▪ Societal impact assessment can be part of the operational program and community involvement should be sought.

FUTURE DIRECTIONS

CAIPEEX IV has demonstrated that it is possible to increase rainfall in a water-tense area by cloud seeding successfully. CAIPEEX was executed in Solapur, a perennially water-scarce district of southern Maharashtra. A relative enhancement of rainfall in seeded clouds compared to the no-seeded clouds as part of the randomization experiment is illustrated through the hygroscopic seeding technique. It was found that an enhancement of rainfall could be ≅46±13 percent as per rain gauge observations and ≅18±2.6 percent as per radar observations over an area of 100 square kilometers.

The project's success was driven by meticulous and well-planned experiments and observations, i.e., by choosing the right seedable clouds as per the protocols. The hygroscopic cloud seeding was conducted by standardized methods backed by robust data recording and analysis. A high-resolution numerical model was used for guidance for seeding area selection and assessment of the seeding impact.

We must not underscore the complexity and uncertainty in targeting convective clouds, assessing the seeding impact, and tracing seeded rainfall on the ground, with hygroscopic seed particles. A center of excellence can be set up at the IITM, Pune, to function as a nodal facility to plan and provide technical guidance for successful cloud seeding programs to cater to the needs of various water-scarce locations in India.

The center should be mandated to conduct specialized studies on cloud physics and weather modification to enable policymakers and stakeholders in mitigating issues such as scarce rainfall.

Currently, most of the technology and equipment required for conducting cloud seeding is imported to the country. The center at IITM should facilitate the indigenization of technologies for cloud seeding aligned with the Make in India vision of the Govt of India. Moreover, the center should evaluate the feasibility of adopting newer technologies such as drones and flares made using nanotechnology in India and instrument development with industry collaborations for cloud seeding and monitoring. Continued research is needed to test more efficient seed particles (flares) which can form cloud droplets at considerably low relative humidity conditions.

The center should also work towards expanding international collaborations in cloud physics research and modification. The center should explore multiple facets of cloud seeding and weather modification. This includes basic and applied research based on laboratory studies and numerical simulations, development for cloud seeding flares, testing facilities for flares such as cloud chambers, advanced decision-oriented unmanned vehicles, and improving decision support systems, including the use of AI/ML for cloud selection and identifying suitable modes of intervention.

KEY POLICY POINTS

1. What is the best way to execute cloud seeding over a rain shadow Indian region during the monsoon season?

CAIPEEX has shown that hygroscopic seeding near the cloud base can enhance rainfall in a rain-shadow region in Indian tropical settings. Warm convective clouds should be seeded when they are in their growing stage using hygroscopic flares targeted to the cloud base by an aircraft. The other method of cloud seeding, that is, glaciogenic cloud seeding redistributed rainfall over a wider area, and had a non-discernible impact on rainfall at the CAIPEEX experimental location.

3. Is it commercially viable? Whether cloud seeding can help mitigate drought conditions for agriculture and drinking water?

CAIPEEX IV yielded 18% enhancement of rainfall and that meant approximately 8.4 million liters of water per flight, which was conducted in all available conditions with the scientific protocols set in the experiment. 18 Paisa per liter of water made to rain, considering the operating cost of 15 lakh per seeding flight. The demand-supply gap can be addressed with catchment scale cloud seeding. This may not help mitigate drought with cloud seeding alone, but it can possibly help in managing drought conditions with catchment-scale projects. Cost can be considerably reduced by use of indigenous aircraft and equipment.

5. Should state governments follow cloud seeding whenever a region becomes rainfall-deficient and water-stressed?

Hygroscopic cloud seeding should be adopted to enhance rainfall in rain-deficient and water-stressed areas in Indian settings under suitable conditions, backed by statistical, physical, and numerical evidence as elaborated in this document. However, there are large uncertainties are depending on the cloud dynamics and background aerosol content. A science-based approach to cloud seeding will be mandatory.

Annexure A: INFRASTRUCTURE REQUIREMENTS FOR HYGROSCOPIC CLOUD SEEDING

S No	Equipment	Purpose	Estimated cost (INR crores)
1	Ground-based radar with an optimum scan strategy, preferably dual-polarized C-band	Monitoring, identifying target areas, and evaluation of cloud seeding. Hygroscopic seeding targets clouds with warm bases and it is required to plan radar sites close to (a minimum of 10 km) the target area. Phased array radars would prove to be more efficient in the future for rapid scans.	12
2	Rain gauge network with at least one ARG per 25 km^2	Monitoring and measuring the amount of rainfall in an area.	3
3	Radiosonde and Celiometer or Combination of wind profiler and radiometer or	Conducting thermodynamic measurements.	3
4	Decision support system	Planning and execution of the daily seeding operation with details on the assessment for probable locations and types of clouds, target time, cloud base height, etc, with an estimate of the uncertainty.	0.25
5	Cloud seeding aircraft (Hiring cost depends on the type of aircraft)	Conduct measurements and cloud seeding with onboard equipment such as seeding flare racks, and instruments to measure basic cloud physics, updrafts, and liquid water, with a data logging system.	15
Total upfront cost per site (as points 1-4 amount to a one-time investment)			33.25
6	Other annual costs	Maintenance of equipment, instruments, engaging manpower, research, and development, Telemetry for radar etc.	5
Total cost per site including upfront costs			**38.25**


Picture: Research Aircraft (Beechcraft B200) with instruments used in the experiment (left) and an automatic range gauge used in CAIPEEX IV (right).

Annexure B: ESTIMATION OF COST BENEFIT

The CAIPEEX IV has shown a relative enhancement of accumulated rainfall in convective clouds over two hours after seeding over a 100 km^2 area downwind of the seeded location to be 46 percent as per automatic rain gauge measurements and 18 percent as per radar data. The daily average rainfall in the 100 km^2 downwind area of seeding has shown a relative enhancement of 18 percent in rainfall, which is approximately 8.67mm. Converting to per unit area (x 1 litre m^{-2}) equals 8.67 litre m^{-2} for seed samples. This relative enhancement over 100 km^2 area in square meters (8.67×10^8 m^2) is 867 million litre of water.

The cost of CAIPEEX IV (for hiring the aircraft and conducting the experiment; note that suitable aircraft, which can fly to an altitude of 8 km for seeding was not available in the country) is approximately INR 36 crores for hiring two aircraft for 480 hours of flying. The operational cost per flight is, therefore, approximately INR 15 lakhs. Each seeding flight duration is on average 4 hours, depending on the aircraft's endurance. On average, the aircraft could do four seeding events in four hours during the experiment. The number of seeding events could be more in an operational project. The operational seeding could be carried out with one aircraft in small catchment areas. The cost can be considerably reduced with the availability of seeding aircraft within the country.

In CAIPEEX, there were 103 seeding flights for the randomization experiment. There were 8.42 million liters of water enhancement per flight

Relative enhancement in rainfall	18 %
Total enhancement in water	867 Million Liters
Number of flights	103
Operating cost per flight	15 lakhs
Enhancement per flight	867/103= 8.42 Million Liters /flight
Approximate cost of producing water by cloud seeding	15 Lakh/8.42 Million liters = 0.18 Rs/Liter = 18 paisa / Litre

Solapur Municipal Corporation distributes 150 MLD of water. They have a demand-supply gap of 56 MLD. The exact cost of water supply in Solapur is to be estimated from the present scenario. Considering the expenses associated with the artificial production of rainfall in CAIPEEX, which involves advanced scientific instruments for research and cloud seeding evaluation, there is a potential for cost reduction to address the gap in water demand within the operational cloud seeding program.

Parameter	Value
The average water supply of Solapur, Maharashtra	168 MLD
Demand for water	224 MLD
Demand-supply gap	56 MLD (84 MLD in peak summer months)
Supply frequency	Every 3 days
Sources	Ujani Dam: 65 MLD Aunj Bandara-Bhima river Takali filter plant: 75 MLD Hipparga/Ekruk Lake, Bhavani Peth filter plant: 9-10 MLD
Revenue of water during the year of experiment	Approx. INR 37 crores per year

Source: IDARC report, 2019: Integrated Catchment Management Plan for Ekrukh Micro-Catchment at Solapur, Maharashtra.

Annexture C: FOUR-STAGE PLAN FOR OPERATIONAL CLOUD SEEDING PROJECTS

1. ASSESSMENT	2. PLANNING	3. OPERATIONS	4. EVALUATION
The decision for seeding or no-seeding	Planning for cloud seeding	Executing cloud seeding	Work post-cloud seeding
Use probability, ensemble and extended range forecasts, large-scale predictors of drought, climatology of drought conditions over the area, extreme rainfall events, etc. to assess the need for seeding.	Arrange cloud-seeding aircraft, instruments (such as radar, radiosonde, rain gauges and basic aircraft instruments for measuring liquid water content and vertical velocity), equipment for seeding and tracking, and flares, manpower, etc. Obtain clearances and certifications for aircraft and flares.	Conduct data quality checks and calibrate all instruments during the entire program. The radar should be operated with minimum scan time to track clouds of interest without delay.	Gather data and perform quality checks. Conduct meetings with scientists to improve methodology and assess outcomes. Publish a report on the outcome with results backed by observations.
Develop /use a numerical model based decision support system. Choose target areas and clouds with numerical modeling and radar observations.	Include weather forecast model and decision support based on the seeding protocols. Develop a seeding strategy for clouds based on all available information and obtain necessary permissions for the flight.	Use radar observations to find suitable region with seedable clouds. Communicate with radar operator to select clouds as per protocol for seeding.	Post-process model outputs together with radar data for a detailed evaluation of the seeding operation. May establish collaborations if required to carry out this goal.
Make ground observations with a dedicated radar and ARG network to estimate probable areas and locations of rainfall.	Study and record cloud and rainfall climatology, atmospheric moisture, diurnal cycle, and any large-scale weather over the target area.	Document each seeding event with details of time, latitude, longitude, seed particle type, burning time and rate, and ambient conditions (cloud base, cloud top, freezing level, etc.).	Evaluate outcomes of cloud seeding. ▪ Cost-benefit ratio. ▪ Local to regional effects. Extra area effects.
Make well-advanced plan to gather adequate time for	Choose an evaluation area with similar meteorological conditions as that of the target site. Evaluate an	Conduct routine pre-flight briefing and post-flight debriefing.	Document and publish outcomes through reports and publications.

arranging and handling resources such as airports, permissions, trained manpower, cloud seeding operators, administrators, disaster management groups, economic impact assessment groups, PRO, etc.	advance plan by various groups including those which may not be directly involved in the seeding experiment. Use a randomization method to test the efficacy of seeding. Strategize to update the public through media, social networking, press briefs, etc.	Rainwater chemical analysis could be conducted periodically in the seeded area. Ensure data quality through periodic evaluations during the operations	Provide regular reports in the public domain. Conduct environmental impact assessment if long-term work is planned.

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Picture: Solapur Airport, from where CAIPEEX IV was conducted (left) with aircraft used for CAIPEEX IV (right)

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