CAIPEEX

CLOUD AEROSOL INTERACTION & PRECIPITATION ENHANCEMENT EXPERIMENT

Science Plan

Indian Institute of Tropical Meteorology

Pune

CONTENTS

1 Background and Motivation of CAIPEEX

Indian Summer Monsoon Rainfall (ISMR) shows large interannual and intraseasonal variability. Spatial distribution of coefficient of variation of ISMR shows values of 40 to 100 % over peninsular India. ISMR is also low over this region. This region is one of the most vulnerable regions of ISMR. During the weak monsoon years, acute water shortages prevail over the region. To alleviate the stresses generated by water shortages, cloud seeding experiments for rain enhancements have been carried out by state governments of Maharashtra, Karnataka and Andhra Pradesh in recent years. Generally, weather modification experiments for rain enhancements are carried out over different parts of the world for a wide variety of applications such as water resource management, hydroelectric power generation and agriculture.

Precipitation efficiency, defined as the ratio of the rate of rain reaching the ground to the flux of water vapor passing through the cloud base (Marwitz 1972), ranges from zero in non precipitating clouds to greater than unity for short times in very intense convective systems (Cotton and Anthes 1989). Some of the ordinary thunderstorms transform less than 20% of the influx of water vapor into rain on the ground (Braham 1952). Most of the water vapor is lost in the anvils of the clouds. As per the recent study by Gambheer and Bhat (2000), the active Cb clouds occupy about 10% of the area and the remaining area is occupied by the anvil clouds. In monsoon season, the precipitable water at any day at any place is about 5 cm. Average daily rainfall (84 cm / 122) is about 0.7 cm. This simple calculation shows that only 10% of available moisture is converted into rainfall.

The principles of most, if not all, precipitation enhancements hypothesis are rooted in triggering the precipitation earlier in the cloud, without allowing clouds to get transformed into anvil stage or without allowing to get dissipated. This eventually results in improvement of efficiency of cloud precipitation.

Precipitation initiation and development in clouds can proceed via several physical paths (figure1.1) involving various microphysical processes that proceed simultaneously but at different rates, with one path becoming dominant because of its greater efficiency under given atmospheric conditions.

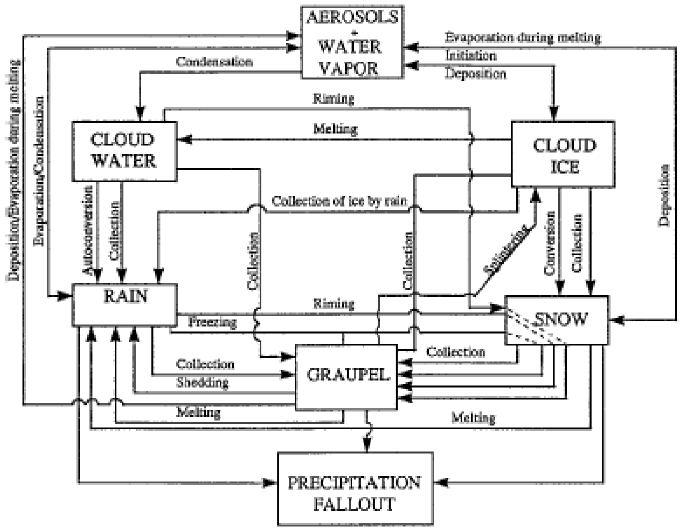

Figure 1.1 Various pathways by which water vapor is transformed into various types of cloud particles and precipitation. Adapted from Houze (1993, 96).

The efficiency with which clouds produce rain at the surface varies greatly. The understanding of these processes is very essential for rain enhancement programmes. The subject of cloud seeding for rain enhancement can be considered as a part of the cloud microphysical studies. The cloud seeding has been a controversial subject from the very beginning. The reason being the complex nature of the cloud-rain processes, lack of ground measurements, limited number of samples, strong natural variability in the large scale atmospheric conditions etc.

The potential for increases in rainfall using cloud seeding is strongly dependent on the natural microphysics (size and concentration of water droplets and ice particles inside clouds) and dynamics (forces affecting air motions in and around clouds) of the clouds that are being seeded. The microphysics in turn dependent on background aerosol levels, because it is the aerosol particles that attract water vapor to form cloud droplets, and in cold clouds, ice particles. Furthermore, the types and concentrations of aerosol particles can be influenced by trace gases (i.e., air pollution). Given these dependencies, the microphysics of clouds can differ significantly from one geographical region to another, and even between seasons in the same region. In some instances, clouds may not be suitable for seeding, or the frequency of occurrence of suitable clouds may be too low to warrant the investment in a cloud seeding program. Both factors need to be evaluated in a climatological sense.

It is therefore essential to understand atmospheric aerosols and pollution levels and their effects on the microphysics and dynamics of naturally forming clouds. This will help to design the seeding experiment subsequently. If the targeted measurements and additional data show sufficient evidence for clouds to be positively affected by cloud seeding, the cloud seeding techniques should then be evaluated using a randomization procedure to statistically demonstrate that the seeding method works, and to quantify any possible increases.

The variability in ISMR has been due to many nonlinearly interacting physical processes associated with the ocean-atmosphere, land–atmosphere linkages. The local topography also adds complexity to monsoon variability. On one hand the climatological mean summer monsoon rainfall shows a robust feature with mean ~ 84 cm and SD of 8 cm which provides enough evidence of existence of adequate CCN distribution and rainfall processes to occur naturally. While on other hand, there are break monsoon conditions, in which these naturally occurring rainfall processes are inhibited because of large scale processes. Even during break conditions a good amount of cloud population is present however they fail to precipitate.

The basic assumption by which the seeded clouds could enhance the precipitation is that they accelerate the collision-coalescence process through introduction of seeds of larger diameter which modify the droplet size spectrum towards larger droplet sizes. Though it looks simple, there are number of points over which our understanding is in adequate. Therefore it is very difficult to isolate the effect of the seeding in naturally growing clouds.

During the weak monsoon conditions, there have been demands for the cloud seeding operations for rain enhancement. The operational programmes carried out in the last few years by various state governments were not scientifically planned also no observations of environment as well as clouds were taken. Hence no conclusions could be drawn regarding the impact of the seeding.

The positive results in Indian Institute of Tropical Meteorology (IITM)’s past cloud seeding experiments have been taken as the basis for carrying out the operational programmes. There are many factors which limit the use of these results in the present scenario. During the past 30 years, after the IITM’s experiments, there are large changes in the atmospheric constituents due to anthropogenic activities and increase in pollution (aerosols) levels.

In this situation there is a strong and urgent need for a definitive and authoritative conclusion to be drawn primarily for the scientific reasons to understand different pathways and secondarily to provide science based guidance to state governments and other social organizations who consider seeding as a solution to mitigate the drought conditions.

A coordinated sustained national programme of cloud studies designed to reduce the knowledge gaps in the cloud microphysics is required. Cloud seeding experiments can be a part of major cloud physics programme. For addressing the questions stated above, a carefully designed experiment with all the cloud microphysical measurements along with the large scale atmospheric conditions in which the clouds are embedded is required. Aerosols play an important role in the earth-atmosphere energy balance and cloud formations. Thus additionally, there are requirements of aerosol observations for understanding aerosol-cloud interactions.

To address these problems, special cloud, aerosol observations over different parts of the country are essential. In this regard scientific and technical resources in the country are required to bring together to have an observational programme to focus on the key uncertainties in aerosol distribution and rain formation processes.

2 Cloud- Aerosol Interactions

2.1) Introduction

Understanding of clouds, aerosols and their interaction is very essential for conducting the precipitation enhancement experiment. The interactions occur both ways, clouds influence the aerosol distribution and aerosols influence the cloud distribution. Aerosols play important role in affecting the individual clouds as well as large scale atmospheric fields through their absorptive and reflective properties. Large scale atmospheric conditions are determining factors for the formation of convergence and divergence patterns which in turn are responsible for cloud formations and further growths.

Cloud physicists have traditionally designed clouds as “maritime” and “continental” based on their microphysical characteristics. Maritime clouds contain small concentrations of (about 50 to 100 cm^{-3}) large droplets and continental clouds contain larger concentrations of smaller droplets. The difference has been due to the large differences in the concentrations of cloud condensation nuclei (CCN) over land and ocean. Maritime clouds precipitate easily by warm processes, whereas coalescence is often suppressed in continental clouds, which often have to grow to supercooled levels to precipitate by cold processes. The boundary layer air is drawn into the base of clouds during the formative process. The boundary layer air, as well as free atmospheric layer air is clean over oceans whereas it is very much polluted over the continents. These large quantities of aerosol concentrations are the source of large number of CCN in continental clouds. The continental aerosol concentration is extraordinarily variable. Therefore it is prerequisite condition to have knowledge of CCN and aerosol concentrations in different types of synoptic conditions during monsoon season.

Aerosol affects clouds by modifying the large scale environment through changing of energy balance of the atmosphere. Numerical experiments from general circulation model (GCM) have suggested that atmospheric circulation anomalies induced by black carbon from coal burning may be a cause of long term drought over northern China, and excessive rainfall over southern China and India (Menon et al 2002).

Recently Ramanathan et al (2005) showed that on climate change time scales, as a result of blocking of solar radiation reaching the surface by aerosol i.e. global dimming, the earth surface cools, leading to a gradual spin-down of the tropical water cycle and eventually weakening of Asian monsoon.

Lau and Kim (2006) have shown that aerosols play significant role in the subseasonal variation of the monsoon activity. They proposed 'Elevated Heat Pump' (EHP) hypothesis. In simple terms, it may be stated as "radiation absorbed by aerosols at upper levels acts as heat source for the atmospheric circulation". They showed that increased loading of absorbing aerosols over Indo-Gangetic Plain in pre monsoon season is associated with (a) increased heating of the upper troposphere, with a formation of a warm-core upper level anticyclone over the Tibetan Plateau in April May, (b) advance of the monsoon rainy season in northern India and (c) subsequent increased rainfall over the Indian subcontinent and decreased rainfall over East Asia in June-July.

During break periods, westerly anomalies are observed over Indian land mass from surface to middle levels. These westerly anomalies are associated with the large concentrations of Arabian desert aerosols. Also due to lack of precipitation, the soil over Indian land region becomes dry and serves as source of dust and aerosols. Thus there is large amount of loading of aerosols during break monsoon conditions. There is lack of understanding regarding the space-time distribution of aerosols during the phases of monsoon season.

2.2) Aerosol studies in India

Direct radiative effects of aerosols have been reasonably understood over Indian sub-continent after INDOEX experiment (Jayaraman et al. 1998, Moorthy et al. 2004, Pandithurai et al., 2004, Pant et al., 2006, Ramanathan et al. 2001, Satheesh and Ramanathan, 2002; Singh et al. 2005, Tripathi et al. 2005). Observational study of aerosol indirect effects (i.e. aerosol-cloud interactions) is almost none over the Indian sub-continent.

IITM developed a unique long-term dataset of aerosol vertical profile over Pune using a bistatic Argon ion lidar and established a climatology. A study has been made to understand role of aerosols by correlating the premonsoon aerosol loading with ensuing monsoon rainfall (Devara et al., 2002; Devara et al., 2003).

ISRO GBP initiated a programme on the topic "Atmospheric aerosols, Radiation and Climate Effects" to understand the sources and composition of atmospheric aerosols and their role in modifying the climate. Under this project, ISRO organized 3 major campaigns on atmospheric aerosols to characterize the natural and anthropogenic sources for bringing out national level aerosol optical depth (AOD) maps of the whole country on a periodic basis. In addition to the local sources by virtue of their atmospheric dwell time of 7-10 days and transport from the marine, continental sources as well as inter-continental transport makes it complicated in understanding the aerosol transport and composition over the Indian region.

In the above direction, ISRO-GBP has undertaken a mobile pilot land aerosol campaign during 1st-28th February 2004 covering 15,000 km road length in southern India through participation of 10 national institutions.

As a follow up of this pilot land campaign ISRO GBP organized another campaign over Indo-Gangetic plains (Hissar, Delhi, Agra, Kanpur, Kanpur, Allahabad, Nainital, Jaduguda and Kharagpur) through continuous measurements of aerosols for a period of entire 1st - 31st December 2004. During these campaigns, vertical profiles of black carbon aerosols were obtained in Hyderabad and Kanpur with NRSA aircraft and IIT Kanpur aircraft, respectively (Moorthy et al., 2004; Tripathi et al., 2005). In addition to the above campaigns, ISRO conducted an integrated campaign for aerosols, gases and radiation budget (ICARB), a muli-instrumented, multi-institutional, multi-platform field campaign of ISRO-GBP. In the above experiment, segmented approach was used to obtain the spatio-temporal information, which will then have to be integrated. Accordingly, the ICARB had the following segments:

The land segment – comprising of a national network of aerosol and gas observatories spread across the mainland and islands (spread from Thiruvananthapuram to Kullu, Patiala to Dibrugarh, and islands, Minicoy and Port Blair)

The ocean segment – constituting extensive and carefully designed cruise measurements over the Bay of Bengal (BoB), Tropical Indian Ocean (TIO) and

Arabian Sea (AS), during the same period, and

The air segment – making measurements of the altitude profiles of aerosol parameters and trace gases, from different coastal and inland stations, around regions covered by the network/ cruises as close as possible to the other measurements.

The above experiment was conducted during pre-monsoon and the campaign period was selected based on the following criteria:
Season during which atmospheric lifetime of aerosols is sufficiently long.
The season should have a good probability of clear sky occurrences so that a good amount of sun-photometer data as well as outdoor aerosol samples could be collected over the entire sub-continent.
The season should have a low probability of occurrence of weather phenomena like cyclones and deep depressions, so that the spatial distributions of the aerosol characteristics can be reasonably assumed to be temporally stationary.
Precipitation should be weak. They conducted 26 sorties from 5 bases (Bhubaneswar, Chennai, Thiruvananthapuram, Goa, Hyderabad). Instruments operated from the aircraft for aerosols included a micropulse lidar, an Aethalometer, an optical particle counter, a scanning mobility particle sizer, an integrating nephelometer, an ozone analyzer and a GPS receiver.

The above experiments, where in IITM was also one of the participants, focused mainly on direct aerosol radiative effects and did not focus on aerosol-cloud interactions. Hence, simultaneous measurements of aerosols and cloud microphysics are essential to delineate the effect of aerosols on clouds and precipitation.

Aircraft observations of the aerosol number concentration and size distribution upto 12.5 km were done (Reus et al. 2001) over Indian Ocean in the Indian Ocean Experiment (INDOEX) programme. In Arabian Monsoon Experiment (ARMEX-1) conducted in August 2002, aircraft observations of number concentrations of aerosols have been carried out at an altitude of 6 km by AN-32 aircraft of the Indian Air Force. The study by Murugvel et al (2005) showed that at the top of the mixing layer, aerosol size distribution was bimodal or trimodal. Kamra et al (2003) measured aerosol size distribution over Indian Ocean during the INDOEX in winter monsoon seasons of

1998 and 1999. They observed a large aerosol concentration ranging between 4X 10^2 and 10^4 cm^{-3} over the north Indian Ocean in the winter monsoon season. Aerosol concentrations are much higher towards the north of the ITCZ. The monomodal size distribution of the particles observed near coastline gradually becomes more and more organized into bimodal distribution as one proceeds from north to south.

2.3) Cloud Microphysics studies at IITM

IITM in 1967 launched well organized programmes of laboratory experiments and field studies aimed at understanding the microphysics of convective clouds and precipitation mechanisms. A 3-cm weather radar was installed at Rain and Cloud Physics Research (RCPR) unit Delhi in 1967. Since that time RCPR has been engaged in conducting radar observations of clouds to (i) investigate precipitation characteristics/mechanisms in monsoon clouds, (ii) develop a method for radar estimation of rainfall by comparing the intensity of radar echoes and the rainfall measured by rain gauges, and (iii) evaluate cloud seeding experiments. The important results obtained under this programme include:

- During the summer monsoon season at New Delhi, the frequencies of occurrence of warm, cold and mixed (warm and cold) rain processes are 41, 16 and 43% respectively. The contributions of rainfall to the season's total by the above processes are 1.8, 52.6 and 45.6% respectively (Devara and Ramana Murty, 1984).
- Analysis of radar observations made during 1958-80 showed that about 46 % of the convective clouds in the Delhi region had vertical extent exceeding 6 km and might be of cumulonimbus type. Convective clouds with tops exceeding 6 km occurred on maximum number of occasions during May and minimum number of occasions in December. In about 95% of the convective cloud the height of cloud-tops was limited to 12 km and in about 0.7% cases it exceeded the tropopause. The maximum echo-top height observed was about 20 km.
- A study relating to 28 cases of clouds during the year 1981 suggested that the growth and decay rates of clouds were in the range -.6-18.3 m/sec and 1.7-15.3 m/sec respectively. The average duration of convective clouds was about 40 minutes.

- Comparison of 24-hour point rainfall as measured by rain gauge and radar indicated that out of 106 point-measurements, radar under-estimated the rainfall in 73 cases and over-estimated in 33 cases.

Besides precipitation, many cloud microphysical parameters like drop size spectrum, liquid water content, phase of hydrometeors, vertical motion in clouds are of much interest which can be derived from the radar measurements. Non-precipitating clouds, however, are usually poorly detected at the wavelengths used in operational radar networks. These can be better studied at higher frequencies at which cloud size hydrometeors respond. Light precipitation can also be observed at higher frequencies. Even in phenomena involving heavy precipitation, high frequencies are suitable for observation at close range, as light and portable radars are available in these frequencies which have several advantages for cloud observations at short range. These radars emit low power, which is adequate because of the high reflectivity and short range, and are light and small and are portable. They have high sensitivity at a short range like 10 km. They have quite narrow beams and spatial resolution as high as a few meters with a small antenna and are not affected much by the ground clutter.

The Ka band (8.6 mm wavelength; 35 GHz) radar has been extensively used for cloud and precipitation studies. Pasqualucci et al. (1983) developed a radar in this band with linear and circular polarization capabilities for cloud and precipitation studies. The attenuation is a linear function of the LWC which can therefore be determined, as the contribution from hydrometeors.

IITM has proposed a study of characteristics of the tropical clouds during different phases of convection over the different land stations by employing the mobile Ka band radar system in the 11 five year plan. For understanding the large scale flow and cloud –atmosphere interaction, X band radar is also proposed.

3 Precipitation Enhancement Experiments

3.1) Indian Status

In India, cloud seeding studies started immediately after the pioneering work by Vonnegut (1947). Initial attempts in the cloud seeding were made at Kolkata in 1952 by late Dr. S. K. Banerji. The technique consisted of dispersing seeding agents like salt and silver iodide by means of hydrogen filled balloons released from ground. Some attempts were made by Tata firms in 1951 to seed clouds in the Western Ghats region using ground based silver iodide generators. RCPR unit of IITM carried out randomized warm cloud modification experiments through salt seeding during 1957-1966 in north India. The results of the rainfall analysis showed statistically significant increases by about 20% on seeded days (Ramana Murty and Biswas 1968).

Randomized salt seeding experiments with fixed control-target design were conducted using ground based generators at Tiruvallur (Tamilnadu) during the SW and NE monsoons of 1973, 1975-1977. The results of these experiments suggested an increase of 32% during SW monsoon and decrease of 17% during NE monsoon (Pillai et al. 1981).

The effect of massive salt seeding on warm maritime cumulus clouds has also been studied. A few clouds were seeded using aircraft within 50 kms of the coast of Mumbai during monsoon seasons of 1973 and 1974. During these experiments radar and in-cloud electrical, microphysical and dynamical observations were made (Chatterjee et al 1978). The radar observations indicated increases in areal echo coverage, vertical extent and echo intensity following the release of salt particles into the clouds.

3.1.1) Randomized experiments

(a) Delhi Experiment

Two major randomized warm cloud seeding experiments were carried out in India. The first experiment (Delhi experiment) was carried out during 1957-66 in the Delhi, Agra and Jaipur regions located in the plains of northwest India. Seeding was carried out during the summer monsoon months of July to September when the prominent clouds were cumulus and stratocumulus with their tops not exceeding the freezing level. A fixed control - target design with day randomization was adopted for the experiment. A brief summary of the design and the details of the seeding methodology used in the experiment are described in the following.

The areas of the target and control sectors in the three regions varied between 450 and 1270 km^2 and the density of the rain gauge network varied from 1 gauge per 50 - 300 km^2. Seeding was carried out either by spraying from the ground a dilute salt solution using power sprayers and air compressors, or by dusting a finely powdered mixture of salt and soapstone in the ratio 10:1 (Biswas et al., 1967). The median radius of the salt particles was 5 µm. The estimated dispersal rate at the source was approximately 2 x 10^{10} salt particles (radius 5µm) per second. The control and target areas were defined upwind and downwind of the central seeding locations and comparisons were made between the rainfall in these two areas for seeded (Target) and not-seeded (Control) days. Seedable days were selected on the basis of certain meteorological criteria, particularly in respect of low cloud amount, wind shear and humidity in the lower levels. Days on which rain occurred frequently or continuously were not considered as seedable days. Hence, it is unlikely that the rainfall recorded in the control and target areas could be from the tall convective clouds extending well above the freezing level which involve ice phase. The above hypothesis is further corroborated from the results of the analysis of 7287 aircraft reports of the meteorological observations of monsoon clouds collected during 1948 - 1951 which indicated that more than 90 per cent of the low cloud-tops lie below the freezing level during the year in India (Pramanik and Koteswaram, 1955).

The results of the statistical analysis indicated increase in rainfall on seeded days, on the average, by about 20 % significant at less than 0.5 per cent level. (Biswas et al., 1967, Ramanamurty and Biswas, 1968). Radar observations of the precipitation development in the clouds in the target and control areas were also made during the later part (1961-65) of experiment. The results of the radar observed cloud areal echo coverage indicated an overall positive result for seeding (Chatterjee et al., 1969).

Delhi experiment has apparently provided the statistical evidence to show that salt seeding may have modified the precipitation in spite of other limitations, e.g.,. ground-based generators used for seeding, lack of the physical evidence in support of the seeding hypothesis. These limitations have been discussed by Mason, (1971), Warner, (1973), Cotton (1982). Warner (1973) argued that the results of experiment are ambiguous particularly due to the lack of the physical evidence in support of a hypothesis that precipitation from warm clouds can be increased through salt seeding technique.

(b) Pune experiment

In order to verify the statistical results obtained from Delhi experiment and for obtaining the requisite physical evidence for the warm cloud seeding hypothesis, a well designed randomized "Warm Cloud Modification Experiment" with good cloud physical measurements programme was carried out in Maharashtra State, near Pune, during the 11-summer monsoon seasons (1973-74, 1979-86). From hereafter this second Indian cloud seeding experiment is referred to as Pune experiment.

A DC-3 aircraft instrumented for cloud physical measurements was used for seeding. The physical measurements carried out in not-seeded (Control) and seeded (Target) clouds were used for documenting the warm cloud responses to seeding (physical evaluation).

Design

A cross-over design having two sectors with a buffer in-between has been adopted. The three sectors have been designated as North (N), South (S), and Buffer (B) sectors (Figure 3.1).

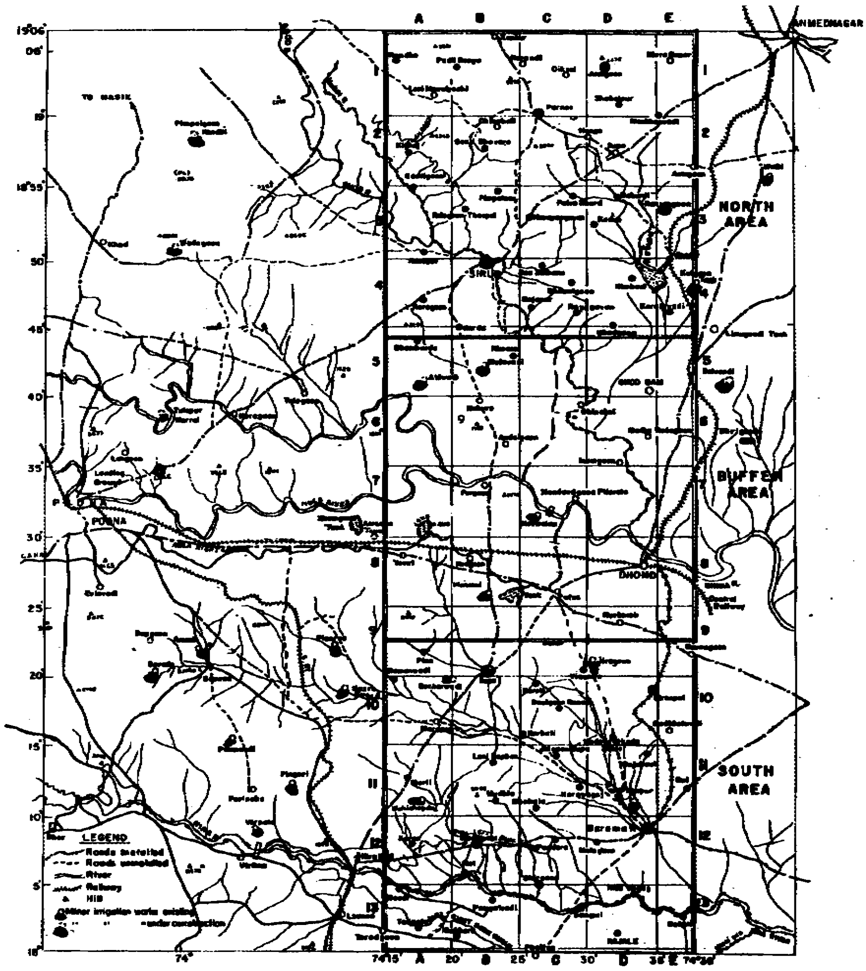

Figure 3.1 Area of Pune experiment

The area of each sector is 1600 km^2. In the crossover design paired target areas are set-up and either area is seeded at random (area randomization), in each test event, the unseeded area serving as the control for that event. The data are obtained in the form of two series. One of the two areas is kept as target in a series and the other acts as control and vice-versa for the other series. The effect of seeding can be obtained from the root-double ratio (RDR) which can be expressed as

$$\mathrm{RDR} = \left(\frac{N_s}{N_{NS}} \frac{S_s}{S_{NS}}\right)^{1/2}$$

where **N** and **S** denote the average rainfall in the North and South sectors and the subscripts s and NS denote the seeded and not-seeded days respectively. When the

North area (N) is allocated for seeding (Target) correspondingly the south area (S) is allocated for not-seeding (Control). Before the commencement of the experiment in each year a series of random numbers (Fisher and Yates, 1953) was taken and used for the allocation of the seeding of the North and the South sectors. Each series used for the experiment in any year was subjected to randomization tests for avoiding any possible bias due to the repetition of the series. In an experiment of sufficient duration the root-double-ratio provides an estimate of the factor by which the mean rainfall has been increased by seeding. The expected value would be close to 1.0 if the seeding has no effect.

The cross-over design minimizes the noise of the natural variability because the fluctuations of the rainfall in the seeded area, to some extent, get neutralized by the parallel fluctuations in the highly correlated control areas. Pair wise randomization scheme is employed with the cross-over design for preventing possible chain of seeding events over the same area, to mitigate the persistence effect and thus prove its sensitivity and efficiency (Moran, 1959). This design is considered to be the most efficient and requires a high correlation between the rainfall of the target and control areas. The provision of the buffer area of the same size as the target and control areas would ensure any possible effects due to contamination.

Experiment Area

The experimental area is located on the Lee-side of the Western Ghats in the Deccan Plateau region at about an altitude of 550 m. It is about 40 km east of Pune (18^{O}32' N, 73^{O} 51'E, 559 m asl) and about 120 km from the west coast at Bombay. The experimental area is perpendicular to the westerly monsoon flow and it consists of three sectors North, South and a Buffer in between the target and control sectors (Figure 3.1). The dimensions of the North, South and the Buffer sectors are identical. The total area of the three sectors is 4800 km^2.

Meteorological Conditions

The experimental area is located in the path of the monsoon westerlies. Prominent weather developments take place in the region when there is a trough of low pressure off the west-coast. The region also experiences rainfall when the axis of the monsoon trough in the mid-troposphere (2.5 to 3.5 km) is situated along a more southerly latitude (19^{O} - 20^{O} N). The experimental area is situated in the semi-arid zone on the lee-side of the Deccan Plateau with the average annual rainfall less than 60 cm. About 80 per cent of the annual rainfall is received during the summer monsoon season (June - September).

Rain seems to fall primarily from the clouds below 3 to 4 km. Once the monsoon is established, the cumulonimbus clouds are practically absent. The freezing level in the experimental area during the summer monsoon months is at about 6 km and a large majority (more than 90 per cent) of the clouds do not reach higher than 5 km (Pramanik and Koteswaram, 1953). Hence, the dominant rain-forming process in these clouds is the collision-coalescence process. There are apparently a number of occasions when the warm cumulus clouds forming in the region do not give any rain.

Rain gauge Network

In the Experimental area 90 standard type meteorological rain gauges were installed and their distributions in the three sectors of the Experimental area are as follows: North Sector (36), South Sector (34) and Buffer (20). In the North and South sectors of the Experimental area, the density of the rain gauge network is about 1 per 40 km^2 and in the Buffer sector it is about 1 per 80 km^2. The above rain gauge network was installed and maintained by the India Meteorological Department (IMD). The 24-hour daily rainfall data recorded by these rain gauges were obtained by the IMD. After scrutiny checks for the reliability of the rainfall data by the IMD, the data were supplied to the Institute for the statistical analysis and evaluation of the results of the Experiment. The 24-hour rainfall measured from 0800 a.m. of the given day (seeded) to 0800 a.m. of the next day was used in the analysis. Various investigators envisage the possible after effects of seeding and therefore, the inclusion of the night following a day with seeding does not seem objectionable (Neyman, 1980).

Rainfall Correlations

Historic rainfall data were available for 6 rain gauge stations located three each in the North and South sectors of the experimental area prior to the commencement of experiment. The six rain gauge stations are part of the national network of the rain gauge stations maintained by the India Meteorological Department. Monthly rainfall data obtained from these 6 rain gauge stations for the 24-summer monsoon (June-September) seasons (1946-62 and 1964-70) were used for the computation of the correlation coefficients (Table 3.1). Mary Selvam et.al., (1978) evaluated the chances of detection of the prescribed increases in the rainfall due to seeding with a specified degree of confidence.

Also, daily 24-hour rainfall data obtained from the 90 rain gauge stations located in the experimental area (North sector 36, South sector 34, and Buffer sector 20) on the 284 days of the cloud seeding experiment carried out during the 11-summer monsoon seasons (1973, 1974, 1976-86) were utilized to compute the correlation coefficients and the results are furnished in Table 3.1.

Table 3.1 : Rainfall correlations of different sectors (North, South and Buffer) in the Experimental Area

Sectors	Correlation Coefficient	Statistical Significance (level-%)	Details of rainfall data used for Computations
North x South	0.7	0.1	Monthly rainfall data for three stations in each sector for 24-summer monsoon seasons (1946-62, 1964-70)
North x South (when north is seeded) North x South (when south is seeded)	0.8 0.8	1.0 1.0	Daily rainfall data of the 90 rain gauge stations in the experimental area for the days of the experiment of 11-years (1973, 1974, 1976, 1979-86)

The results of the correlation coefficients (r) particularly those relating to the daily rainfall data of the 90 rain gauge stations in the experimental area i.e. (r) between North x South when the north and south sectors were seeded (0.8 significant at less than 1 per cent level) can be used as an evidence for the similarity in the rain regimes in the experimental area.

Seeding Techniques and Evaluation Methodologies

Simpson (1978) stated that successful weather modification experiments share three outstanding features, namely persistence through at least two phases, often requiring more than a decade, some type of predictive tool or stratification and a relatively uncomplicated cloud and / or evaluation situation, or by strong target control correlations. The classical approach to obtain statistical significance in the face of high natural variability is to increase the sample size. However, programmes where either the understanding of the complex processes and / or the experimental design were poor, even a hundred years of unevolving randomized experimentation would produce merely additional inconclusive or uninterpredictable statistics. A supplementary alternative which can mitigate the sample size requirement is to make use of information relating to the concomitant variables, i.e. early identification of stratifications, covariates or predictors. Without early identification of concomitant variables, the randomization or operational evaluation would probably fail. Incorporation of a stratification in experiment design can often make the difference between significant versus inconclusive results in a fixed time limit experiment, or alternately can save some years of expensive experimentation.

Most of the successes in weather modification owe a large part of their achievement to identification of concomitant variables, either at the outset or after an exploratory phase of the experiment. It would be satisfying if the predictor or stratification variables arise either from clearly understood physics or model simulations. For the physical understanding and testing of the warm cloud modification hypothesis, seeding and evaluation methodologies consisting of sequential stepwise programmes to test the applicability of warm cloud modification hypothesis, predictor variables and model simulations are to be adopted.

In view of the factors mentioned above the following two types of seeding techniques have been adopted depending on the type of distribution of clouds present in the experimental area on any day of the experiment. The details of the two types of seeding techniques are described in the following.

Area Seeding Technique (Total Target)

On any seedable day when the experimental area is covered with a large number of stratocumulus and cumulus clouds with vertical thickness of 1 km or more and cloud liquid water content of 0.5 gm m^{-3}, the area seeding technique was adopted. On these days of the experiment the seeding material was released into the clouds at a slow rate, (10 kg per 3 km flight path) at a height of about 200 - 300 m above the cloud base, so as to treat as many clouds as possible. The seeding material used on any experimental day for the area seeding covering the whole target area was about 1000 kg. As all the clouds in the target area were seeded it is designated as the 'Area Seeding Technique'. The estimated concentrations of the salt particles artificially released into the clouds during their seeding on the area seeding days could be 1-10 per litre of cloud air.

The flight path followed for this type of seeding is in the form of a loop covering the 40 km width of the target area in about 12 longitudinal tracks viz., 6 tracks during the forward direction and 6 tracks during the return direction of the aircraft flight covered in the target area (Figure 3.2). The seeding operation commences a few kilometers (about 5 to 10 kms) upwind of the western border of the target area. This distance is determined by computing the time required for the transport of the seeded clouds into the target area under the prevailing westerly winds on any seeded day. Similarly the seeding was terminated at a similar distance ahead of the eastern border of the target area in the downwind of the experimental area.

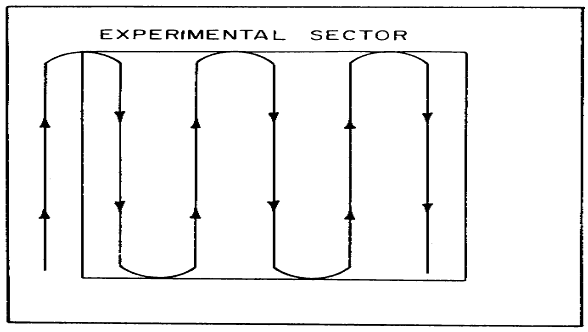

Figure 3.2 The track of the seeding aircraft

The above procedure followed for the seeding of the clouds in the upwind area would facilitate the transport of the seeded clouds into the target area and produce rainfall which can be recorded by the rain gauge network located in the experimental area.

Cloud Droplet Spectra

The aircraft observations of the cloud droplet spectra obtained from 50 pairs of the control and target clouds were analysed and the time variations noticed in the control and target clouds are shown respectively in Figures 3.3 and 3.4. The cloud droplet spectra obtained in the first aircraft penetration were compared to those sampled after 15-20 minutes following seeding. As seen from the Figure there is a marked increase in the concentration of the large size cloud drops (radius 20µm) in the case of the target clouds as compared to that observed in the control clouds. This observational evidence corroborates the warm cloud seeding hypothesis that salt particles released artificially during the seeding of the target clouds have transformed into large size cloud drops which facilitate precipitation formation through the collision-coalescence process. The average concentration of large size cloud drops with diameter greater than 50 µm observed in the control clouds decreased from 0.187 cm^{-3} to 0.073 cm^{-3} in about 15-20 minutes. Similarly the average concentration of large drops in the target clouds, increased from 0.063 cm^{-3} to 0.200 cm^{-3} in about 15-20 minutes. The average Median Volume Diameter (MVD) in the control clouds increased from 9.8 µm to 10.0 µm (2% increase). Similarly in target clouds, the average MVD increased from 8.7 µm to 11.7 µm (increase of 34.8%). The above results suggest that the hygroscopic particles released into the target clouds have transformed into large size cloud drops (diameter greater than 50µm in about 15-20 minutes) following seeding and could enhance the collision - coalescence process leading to the early onset of the precipitation / increase in the precipitation efficiency / rainfall.

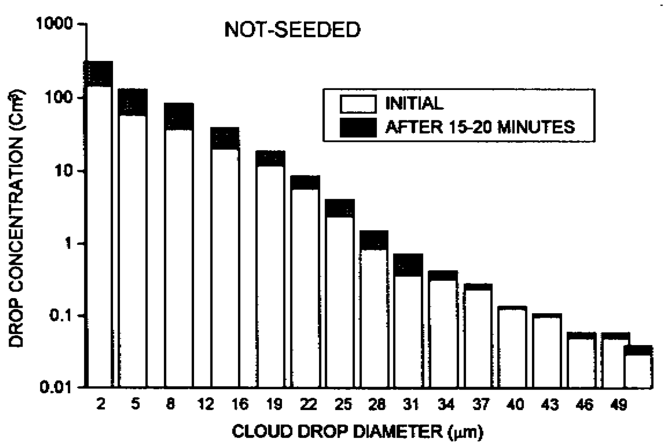

Figure 3.3 Average cloud drop size distribution in not seeded (control) clouds

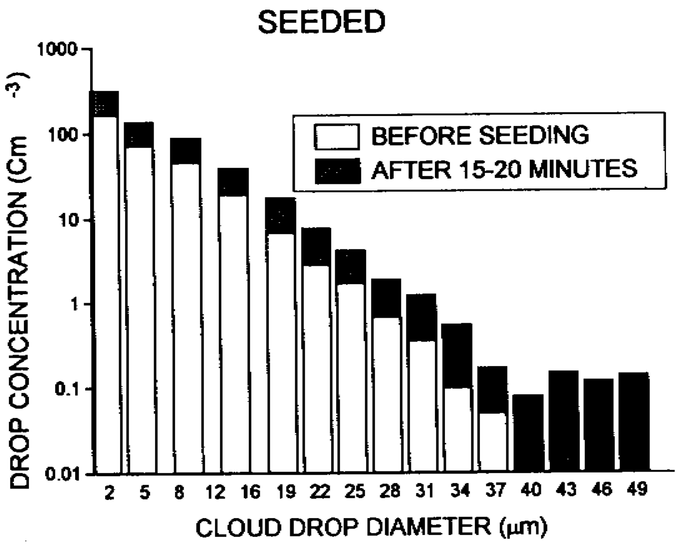

Figure 3.4 Average cloud drop size distribution in not seeded (control) clouds

Liquid Water Content

The aircraft observations of the cloud Liquid Water Content (LWC) obtained from the control and target clouds using the JW-hot wire instrument were analyzed. The observations of the LWC obtained from 60 pairs of control and target clouds were considered in the study. The maximum values of the LWC obtained from the control clouds were compared with the maximum values of the LWC obtained from the target clouds of identical physical characteristics. As already mentioned earlier, the target clouds of identical physical characteristics were selected on random basis and repeatedly seeded. The maximum values of the LWC were recorded in about 10-15 minutes following seeding. The average values of the LWC in the control clouds was 0.6 gm m^{-3} (standard deviation 0.11) and that in target clouds was 1.0 gm m^{-3} standard deviation 0.17). The above results suggest an increase in the LWC of 40% in the target clouds which is significant at less than 1 per cent level. The increases noticed in the LWC are consistent with the preliminary results of individual cases of seeded and not-seeded clouds reported earlier (Murty et al., 1975).

Vertical Velocity

The observations of the vertical air velocity obtained from the 50 pairs of control and target clouds were analyzed. The aircraft flight altitude was maintained constant while collecting the above observations and may be representative of the conditions at the cloud-base level. The maximum positive values of the draft vertical air velocity obtained from the target and the control clouds were compared. The average value of the vertical velocity in the control clouds was 3 m sec^{-1} (standard deviation 1.0) and that in target clouds was 4 m sec^{-1} (standard deviation 1.1). The above results suggest an increase of 33% in the vertical velocity of the target clouds following seeding.

Conclusions

The results of the 11-year Indian warm cloud modification has clearly emphasized the need for the physical understanding, sequential development in the clouds. The results suggested that warm cloud responses to seeding are critically dependent on the cloud physical characteristics e.g., vertical thickness and liquid water content (LWC). Clouds with vertical thickness greater than 1 km, LWC greater than 0.5 gm m^{-3} when seeded with salt particles (modal size 10 µm; concentration 1 per litre of cloud air) produced increase in rainfall of 24 per cent significant at 4 per cent level. Shallow clouds (vertical thickness less than 1 km, LWC less than 0.5 gm m^{-3}) when seeded showed tendency for dissipation. The cloud physical observations made in not-seeded (control) and seeded (target) clouds have provided some useful evidence to test the applicability of the warm cloud modification hypothesis. Results of the cloud model computations suggested that moderate convergence at the cloud-base is essential for the cloud growth and development of precipitation in the real world. Hygroscopic particle seeding of warm clouds under favourable dynamical conditions (convergence at the cloud-base level) may result in the acceleration of the collision-coalescence process resulting in the enhancement of rainfall.

However, subsequent reanalysis of the rainfall data by Ananthkrishnan (unpublished report) did not support the findings of 24% increase in rainfall.

Therefore these results are required to be taken cautiously. The atmosphere is a continuous changing chemical laboratory. The distribution of the aerosols changes on all time and space scales. With this view point, IITM’s past results can not be considered universal and therefore can not be taken as basis for operational programmes in the present situations.

3.2) International Status

The present cloud seeding programmes use modern instruments, air crafts, new seeding methods, radars, satellite observations and numerical models. Typical set up of the present cloud seeding experiment is shown in figure 3.5 (from WMI site). Few details of these are described in the appendix.

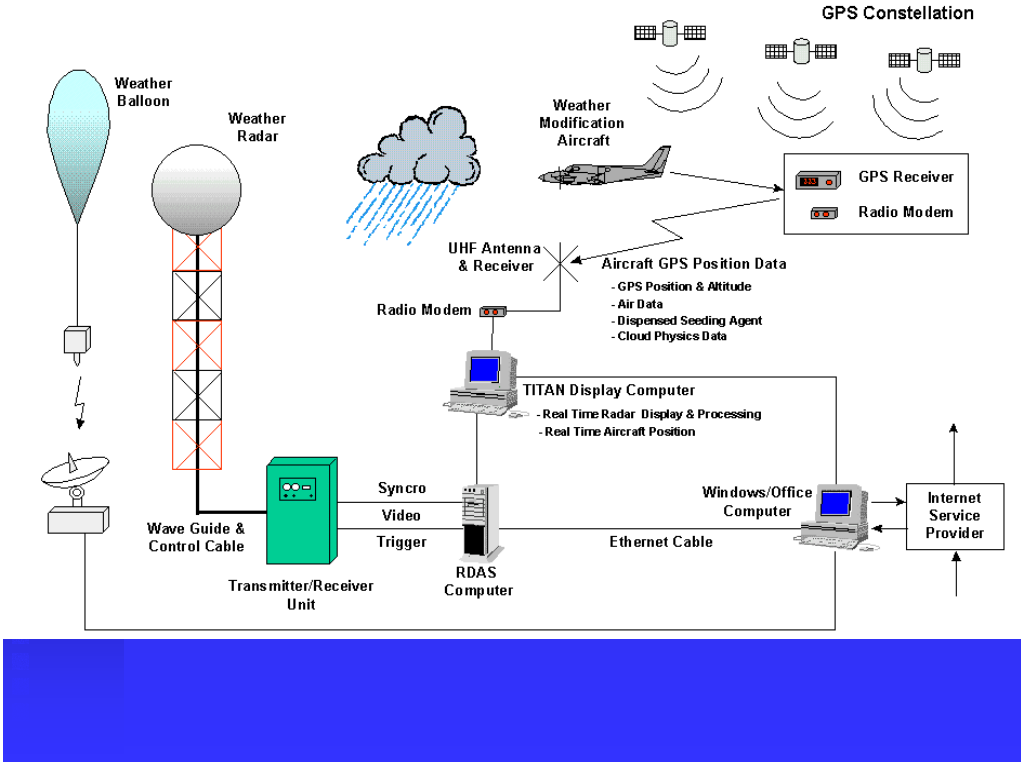

Figure 3.5 Typical set up of the present cloud seeding experiment (from WMI site)

During past ten years, cloud seeding has received a renewed interest. This has especially grown due to the reported positive results from randomized cloud seeding experiment in South Africa using hygroscopic flares. This has led to many other programs around the world to consider these techniques for their research and operational work. A review of cloud seeding experiments to enhance precipitation has been given in Bruintjes (1999), WMO (1999) and Bruintjes et al (2003). As these experiments have triggered the interests of scientists all over the globe, it seems pertinent to understand these experiments in rather details. With this view, South African and Mexican Experiments are presented in this section.

3.2.1) South African Experiment

The seeding hypothesis postulated in South African experiment was:

"Hygroscopic seeding at cloud base accelerates the growth of large hydrometeors in the seeded clouds, which harvest more of the available supercooled water before it is expelled into anvils by the strong updrafts thereby increasing the efficiency of the rainfall process" (Mather et al., 1997)"

The experiment designed to test the hypothesis was carried out during October to March of 1991 to 1995 using following equipments. The air crafts "Weather Bureau Aero Commander 690" and the "Water Research Commission (WRC) Commander 500S" were equipped with seeding racks attached to the rear of the engine nacelles. Each seeding rack held 10 1-kg flares, which were electrically ignited from a firing panel in the cockpit. The aircraft "WRC cloud physics Learjet" was used to make microphysical measurements at around -10°C level in both natural and seeded clouds. The experiments were conducted within about 100 km radius of the two C-band radars located at Bethlehem in the Free State and Carolina (near Nelspruit) in the Eastern Transvaal (Figure 3.6). Both the radars were operated in volume scan mode, collecting a complete scan about once every 5 min.

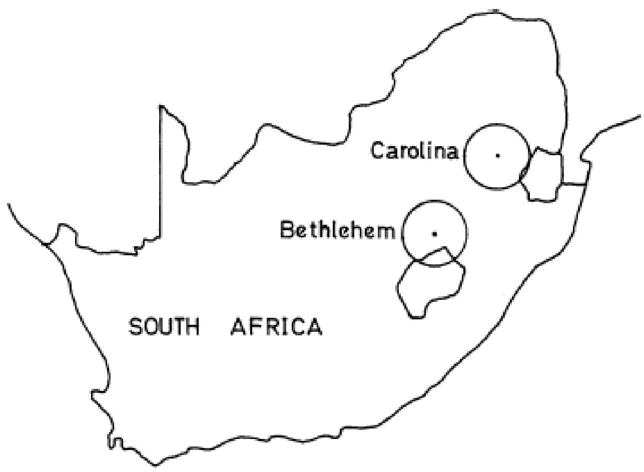

Fig 3.6 Two research areas in south Africa. The circles are centered around each radar and are 200 km diameter.

3.2.2) Design of South African Randomized Experiment

The experiment was designed in conjunction with the Center of Applied Statistics at the University of South Africa (Unisa). Two sets of paired envelopes were prepared at Unisa, one for the Bethlehem and other for Nelspruit experiment. One set of each of the pairs was held in the two seeding aircrafts. Launching criterion was the appearance on radar of two or more separate echoes exceeding 40 dBZ. After take off the seeding and cloud physics aircrafts were directed to the cloud of interest (usually the strongest echo). On finding a suitable updraft, the pilot of the seeding aircraft would confirm with radar operator that the selected cloud is seen by naked eye and aircraft radar. With the above conditions fulfilled, the pilot would declare a case (decision time), at which time the radar operator would open the envelope randomly and communicate the decision to the seeding pilot who would open his envelop. The possible combinations and outcomes are listed in Table 1.

Table 1 Seeding instruction strategy employed to make sure that the radar operator and cloud physics sampling pilots were "blind" as to treatment (seed or no seed).

Radar	Seeding aircraft	Action
Seed	No	No seed
Seed	Yes	Seed
No seed	Yes	No seed
No seed	No	Seed

Since the seeding pilot did not reveal the contents of his envelope, both the radar operator and the cloud physics aircraft crew were blind as to the treatment, eliminating any possible bias in the collection of the radar and cloud physics data. Whatever the outcome, the seeding aircraft stayed with the selected cloud for a minimum 15 minutes after decision time. After completion of the operation, a second cloud was selected which was at least 20 km away from the first cloud.

3.2.3) Results of the randomized South African Experiment

In the 5 year period (1991-1995), there were 127 cases, 62 seeded and 65 controls. The statistical analysis was carried out on the radar derived parameters such as cloud duration, volume, echo heights, rain masses etc. As the cloud size and duration varied largely, the data was divided into quartiles for the analysis purpose. Thus data becomes free from the contamination of the results by outliers. The first quartile is the value that, when the data are sorted in ascending order, one quarter (25%) of the data lies at or below this value and three quarters lie at or above it. The second quartile or median divides the data in half and third quartile lies at the value at which 75% of the data lies at or below this value. The three quartiles of the rain masses of the seeded and not seeded clouds in 10 minutes time window from decision time (t = 0) are shown in fig 3.

Table 2 shows the one-tailed p values calculated to test the null hypothesis that the mean of the seeded clouds is larger than the mean of the controls. The difference is found statistically significant. The analysis found that the smaller clouds are apparently responding to treatment first, the second quartile next and the third quartile last. It is a physically realistic result, since the length of cycle from release of the seeding material at cloud base to its effect on precipitation growth aloft to rainfall on the ground should be proportional to cloud size.

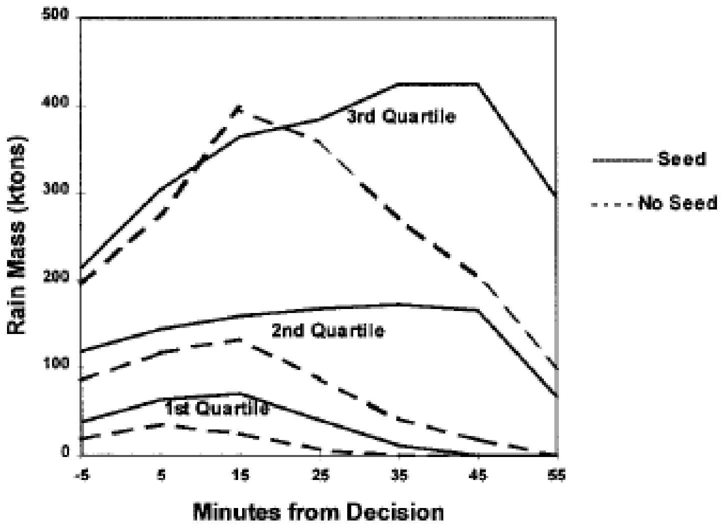

Fig 3 Comparison of the first, second and third quartiles of the seeded vs the control clouds. Note that the seeded clouds peak later and at higher rain masses than their unseeded counterparts.

TABLE 2 Numbers of seeded and control storms in 10-min time windows either side of decision time and the p values for the differences (seeded minus control) of the three quartiles. The p values of 0.10 or less are in bold. The number of storms that are missing and have zero rain mass and the 90% confidence limits for the differences (kton) are shown in parentheses.

Time window (min)	Number of storms: Seeded			Control			One-tailed p values		
	(>0)	(Msg)	(0)	(>0)	(Msg)	(0)	Q_1	Q_2	Q_3
−10 to 0	60	(1)	(1)	59	(1)	(5)	0.22 (−8; 41)	0.20 (−38; 69)	0.34 (−60; 102)
0 to 10	61	(0)	(1)	60	(1)	(4)	0.16 (−8; 62)	0.28 (−38; 76)	0.25 (−93; 166)
10 to 20	60	(0)	(2)	56	(2)	(7)	**0.06** (3; 69)	0.23 (−32; 116)	0.57 (−146; 166)
20 to 30	56	(1)	(5)	50	(2)	(13)	**0.03** (6; 47)	0.14 (−34; 145)	0.40 (−114; 239)
30 to 40	48	(1)	(13)	44	(2)	(19)	**0.02** (4; 17)	**0.03** (34; 178)	**0.10** (−59; 338)
40 to 50	42	(2)	(18)	34	(3)	(28)	— —	**0.01** (34; 179)	**0.006** (72; 412)
50 to 60	37	(4)	(21)	25	(5)	(35)	— —	**0.03** (24; 87)	**0.02** (28; 385)

3.2.4) Bigg's Independent Evaluation of South African Data

In the past, Israel experiments with glaciogenic flares (silver iodide flares) were held highly successful. However, reevaluation of the data by Rangno and Hobbs (1995) showed that the naturally higher precipitation in the north target area on seeded days have been considered as seeding induced change. Thus claim of increase in precipitation due to seeding was rejected. Therefore for demonstration of enhancement of precipitation due to seeding unequivocally, the data has to be analyzed thoroughly and independently. With this objective, Bigg (1997) evaluated the cloud seeding results of the South African experiment independently. He identified following problems / shortcomings in the original analysis.

3.2.5) Problems encountered in South African Experiment

The analysis by Mather et al.,(1997) suggested that there was little difference between rain masses in seeded and unseeded storms until 30 min after seeding. Since the hypothesis demands increased precipitation efficiency in the first 10 min or so after seeding but gives no reason for increased performance thereafter, there appears to be a discrepancy between theory and observation.

- The comparison for times before decision times was insufficiently detailed to give a clear picture of whether seeded and control clouds had similar past histories on average.

- Some indication of the variability in rain masses over a period before seeding commenced would have given a better perspective on the differences that followed seeding.

- The use of arithmetic means for comparison allowed the results to be dominated a few large storms.

- The use of 10 minute interpolation did not take full advantage of the available data and could not give a clear indication of when seeded and unseeded rain masses diverge.

- The storm tracking algorithm of the radar software contained restrictions that caused some large storms to be lost. The causes of this and its influence on the statistics require discussion.

The discrepancy between theory and observation could be examined by using total storm mass (cloud water plus precipitation) instead of rain mass. Improved precipitation efficiency should cause a measurable reduction in this quantity relative to unseeded clouds after first 10 min due to raining out of the cloud water. At the same time the rain mass should show a measurable increase relative to unseeded clouds.

A comparison of cloud masses exceeded by 75%, 50% and 25% of clouds at any time from decision time was made. The comparison (Fig1a, b and c of Bigg) showed that the initial bias of the seeded clouds was removed. The life times for small clouds were prolonged by 10 minutes and 20 min of large storms. The rain mass showed a small peak (fig 2 of Bigg) during 10 min after decision time that was consistent with the "enhanced coalescence" hypothesis. The increase in rain mass was observed in the seeded clouds.

Then he considered the ratio of cloud mass M(t) at time t after decision to the mass M(0) at decision time. There was almost exact agreement between seeded and control cloud mass ratio in the 10 min preceding decision time. The difference became significant after times ranging from 13 to 26 min. This new way of analysis strongly supported that the seeding had a noticeable effect on cloud mass and duration.

A further statistics that was used was the proportional rate of change of mass. In this cloud masses were normalized. The comparison between seeded and control clouds supported the hypothesis.

In conclusion Bigg remarked that the reanalysis using different statistics strongly reinforced the conclusion of Mather et al. (1997).

3.2.6) Independent reevaluation of South African Experiment by Silverman

Silverman (2000) independently analyzed the data for testing the seeding results. In the experiment, the design was changed after the third year by lifting the limit on convective cloud system size and limit on number of flares per convective cloud system. Mather et al (1997) considered all the seeding data from both the locations. How appropriate was to combine data from the two places? Silverman (2000) addressed these points in his analysis. He concluded that

The evaluation of cumulative rain mass as function of time is consistent with the Mather's finding with quartile analysis.

There was no indication that larger cloud systems which were included because of the change of the design affected the results.

Bethlehem cloud systems responded more favorably to seeding than Carolina cloud systems did. The reason stated that the proximity of Carolina to Indian Ocean, provided clouds with maritime nature.

Seeding has no effect on cloud systems whose volumes exceed 750 km^3 (roughly 9X9X9 km size).

3.3) Mexican Precipitation Enhancement Experiment

The promising results of the South African experiment led to a new program in Mexico. It was conducted from 1996 to 1998 using South African hygroscopic flares and in the similar fashion. A four year program was proposed consisting of physical studies and a randomized seeding experiment. During the first field effort in 1996 (July-October), the emphasis was on establishing the infrastructure and operation procedures for collecting data to assess weather conditions and cloud microphysical characteristics in Coahuila. The program was conducted in the state of Coahuila in Mexico bordering central Texas.

A C-band radar was used in the study. The Thunderstorm Identification Tracking and Nowcasting (TITAN) software (Dixon and Weiner 1993) was used for the display of radar data and aircraft position in real time for the purpose of directing the operations. TITAN was also used as the automated evaluation software, objectively defining the experimental unit and producing time series of cloud properties for use in analysis. The aircraft used was Piper Cheyenne, twin engine turboprop airplane, equipped with wing mounted racks carrying 24 hygroscopic flares and a basic cloud physics instrument package.

3.3.1) Design of Mexican experiment

The randomization procedure followed was similar to that used in the South African experiment. The experimental unit was defined as the cloud measured by the radar and tracked by TITAN using a 30 dBZ threshold for a time period of 20 min prior to decision time and 60 min after decision time. Following response variables were chosen:

- Radar estimated precipitation flux
- Total cloud mass
- Cloud mass above 6 km
- Cloud area
- Height of maximum reflectivity.

The hypothesis tested was the value of the response variable larger in seeded clouds than in the non seeded clouds.

3.3.2) Results of Mexican Experiment

Out of total 94 cases, 43 were seeded and 51 were non-seeded. The quartile analysis showed the statistical significance of increase in the response variables in the seeded clouds. The results substantiated the findings of South African experiment.

In conclusions, these experiments have provided the scientific basis for the rain enhancement programme. Flare technology has been used in these experiments.

However, there are different views and opinions exist regarding alternative ways of seeding methodology such as ground generators etc. In the following section, the advantages of flares and airborne methods compared to ground based methods have been discussed.

3.4) Advantages of using flares for seeding

There are various advantages of using the flares for seeding purposes. In the past the seeding material was used to be spread-using funnels fitted with the aircraft. Disadvantages of this approach were that large quantities of salt were needed and dispersion of the salt over areas comparable to a cloud inflow was difficult. Young (1996) pointed out that in the past; most of the seeding material might have been wasted.

There have been suggestions for ground based techniques. The seeding particles are generated by burning organic material in a small pot. The smoke from it is believed to go in to clouds and serve as seeding agent. This mechanism has many pitfalls. Clouds can occur at any place and the probability of generated smoke to go to cloud is very low. The other point is that the atmospheric circulation required must be such that the smoke without dilation has to reach the cloud base. The most important thing is that the seeding material has to go in the updraft regions of the clouds. The ground base technique can not provide guarantee for smoke to have such a path to reach the updraft region in the cloud. Hence ground based technique can not be considered an alternative for flare based technique.

Another alternative suggested is the spray of the water from the top of the clouds. This approach is difficult to implement as very large amount of water will be required to be taken up to high levels in the atmosphere. Moreover, no literatures regarding rates of successes, methodologies etc of ground based and water spray techniques are available in the standard peer reviewed journals.

From the environment point of view, the flare technology is very appropriate. The amount of the salt material spread in one seeding case is only a few kgs. A simple calculations show that this amounts to addition of fraction of micrograms in one cc of water which is very negligible compared with the naturally occurring salt concentrations.

4 CLOUD AEROSOL INTERACTION & PRECIPITATION ENHANCEMENT EXPERIMENT CAIPEEX

4.1) Cloud –Aerosol Interaction

CAIPEEX has two components viz. (1) cloud – aerosol interaction and (2) precipitation enhancement experiment. Understanding of cloud-aerosol interaction is necessary for the second component of CAIPEEX. Aircraft observational programme has been proposed for this. The programme intends to address following key uncertainties in respect with cloud-aerosol interactions:

4.1.1) Cloud/precipitation microphysics Issues

Understand the background concentration, sizes, and chemical composition of aerosols that participate in cloud processes. How nucleation processes relate to characteristics of aerosol particle; ice nucleation; evolution of droplet spectra in clouds; relative importance of drizzle in precipitation processes etc.

4.1.2) Cloud dynamics issues

Understand cloud-to-cloud and cloud-mesoscale interactions as these are related to updraft and downdraft structures in the cloud and evolution, life times of clouds.

4.1.3) Cloud modeling Issues

Problems faced in cloud resolving models for short term prediction of heavy rainfall precipitation. The proposed observational cloud programme will help in validating the cloud simulations.

4.1.4) Seeding related issues

To study the diffusion, transport and spreading of seeding material and its effect throughout the cloud volume. The cloud growth, cloud processes in the seeded and unseeded clouds.

4.1.5) Cloud variability issues

There is large spatial and temporal variability of clouds over India. The convective clouds are predominantly found over Bay of Bengal and north east India. Interestingly, over the west coast of India, where intense rainfall occurs, the clouds are relatively shallow. The rainfall processes in such clouds are poorly known. Similarly the diurnal variation of clouds over different parts of India is not studied in enough details. Such studies are important from the understanding of radiative balance of the atmosphere in the climate studies.

4.1.6) Aerosol distribution issues

Aerosols perturb the radiation balance of the earth-atmosphere system via two different mechanisms viz. scattering and absorption of incoming solar radiation. The scattering of solar energy increases the earth's planetary albedo, thereby cooling the earth's surface. The absorption of solar energy by aerosols changes the atmospheric heating rates, thereby influencing atmospheric circulation. The indirect aerosol effect results in modification of the shortwave reflective properties of clouds, increase of the lifetime of clouds and suppression of drizzle formation (Kaufman and Fraser, 1997; Kaufman, 1995; Rosenfeld, 2000, Koren et al., 2004). Accurate evaluation of aerosol radiative forcing is critical because it can counteract the warming effect due to greenhouse gases (Hansen et al., 1998; IPCC, 2001). Cooling of surfaces and warming of some of upper atmospheric layers due to absorption of solar radiation by aerosols could also change the stability and hence convection.

The air craft and list of instruments used in the study are given in the Appendix.

4.2) Proposed experiment for estimation of potential in the enhancement of rainfall in seeded clouds

4.2.1) Precipitation development in seeded clouds

The continental clouds have high droplet concentrations and narrow droplet spectra at cloud base. The seeding material is dispersed into the region at cloud base. Because these particles are larger and more hygroscopic than the natural particles, cloud droplets will nucleate preferentially on the seeding particles. This inhibits a portion of smaller natural cloud condensation nuclei from becoming activated because the droplets already formed as a result of seeding limit the maximum supersaturation. The result is broader-than-natural droplet spectrum near cloud base that enhances the potential for precipitation to develop earlier and more efficiently in the lifetime of cloud. The seeding effect spreads to other parts of clouds and enhances the formation of precipitation by Hallett-Mossop (H-M) process.

H-M process is well established secondary ice generation mechanism. The primary ice generation process is formation of ice crystals by evaporation of supercooled water and deposition on the ice nuclei. In H-M process the raindrops are frozen when they reach the freezing temperatures. These frozen drops provide more efficient graupel embryos than graupel formed through the primary ice nucleation process. These ice crystals are circulated in the cloud by downdraft and updraft. In this process they breakup providing larger embryos for formation of the drops.

4.2.2) Seeding conceptual model and physical hypothesis

Cloud condensation nuclei (CCN) and Ice nuclei (IN) are the particles that form cloud droplets and ice crystals, a small fraction of which may eventually form raindrops. The objective of hygroscopic seeding is to alter the natural CCN to enhance the formation of the select few cloud droplets that become raindrops while glaciogenic seeding attempts to enhance precipitation formation by increasing ice crystal concentrations and buoyancy effects through the freezing of supercooled water. Thus, actual measurements of CCN and the natural droplet spectra, and ice nuclei and ice formation, should be an important objective of the field program. In addition, ice processes also depend on the characteristics of the cloud droplet spectra.

The effects of hygroscopic seeding are highly dependent on the natural characteristics of clouds and precipitation processes. Physical measurements are therefore important in order to assess which seeding technique should be used and to evaluate the potential effects from seeding on precipitation. It is thus important to design airborne flight patterns for data gathering to answer important questions related to the natural characteristics of clouds. In addition, aircraft measurements of cloud microphysical characteristics will provide a better understanding of the natural processes in clouds. The aircraft data are important to build a climatology of microphysical characteristics of clouds in the region to determine the dominant precipitation formation processes in clouds and the effects seeding may have on these processes. These measurements will also help to validate the model simulations and radar observations.

The measurement / detection of CCN/IN might eventually be used in a real-time operation as a selection criterion for choosing seedable clouds. It could also be used to assess those conditions when seeding would not be expected to be effective. Such measurements will also be necessary during the conduct of a randomized seeding experiment in order to establish one of the physical links between seeding and potential increases in rainfall.

Based on the physical chain of events in the development of precipitation in seeded and unseeded clouds, the seeding conceptual model and hypothesis for microphysical propagation of the seeding effect can be stated as follows:

Microphysical seeding conceptual model

- Hygroscopic seeding broadens the cloud droplet spectra near cloud base
- Enhances the production of drizzle in the updraft regions
- The drizzle particles enter into high liquid water (LWC) regions of cloud
- Above freezing temperatures, graupels are formed which enhances secondary ice generation in the clouds.
- The recirculation of drizzle and fracture components of graupels provide large size particles for triggering the Langmuir Chain Reaction.
- The tiny water drops grow faster to raindrops and thus the rainfall process is initiated

Seeded clouds will differ from unseeded

- Modified droplet distribution near cloud base
- Enhanced drizzle concentrations near tops of turrets
- Enhanced large drop graupel embryos near freezing level
- Enhanced secondary ice generation process

The other seeding technique is *glaciogenic seeding*, in which ice-producing materials (e.g., dry ice (solid CO_2), silver iodide, liquid propane, etc.) are injected into a supercooled cloud for the purpose of stimulating precipitation by the ice particle mechanism. The underlying hypothesis for glaciogenic seeding is that there is commonly a deficiency of natural ice nuclei and therefore insufficient ice particles (~1/liter at –20ºC) for the cloud to produce precipitation with maximum efficiency by the ice particle mechanism.

The conceptual model for glaciogenic seeding is as follows:

- The natural clouds in their developing stages have ice concentrations <1 L^{-1} within their updrafts at the –5°C to -10°C level.
- AgI seeding initiates the ice process earlier in a cloud's lifetime.
- AgI seeding enhances the production of graupel earlier in a cloud's lifetime and at lower levels than natural clouds.
- Graupel produced by AgI seeding provides more raindrop embryos and more rain.
- Additional loading of precipitation at lower levels in seeded clouds results in changes in updraft/downdraft structures and modify dynamic aspects of the storm.

Seeded storms will differ from unseeded storms:

- Enhanced ice concentrations near tops of turrets in feeder or daughter cells as they pass through the –5°C to -10°C level during their growing or developing stages
- Enhanced graupel in the updrafts and then downdraft regions at the edges of turrets
- Enhanced graupel embryos below 0°C
- No differences in the rain drop size distributions between seeded and unseeded storms

4.2.3) Operational procedure

Objective of each operation is to select suitable candidate cloud at random for seeding and to make the measurements required to detect the seeding effect. The seeding will be carried out in randomized manner, as per described in the next section. The procedure is double blind, so the meteorologist at ground and the scientist taking microphysical observations will not have idea about the seeding. Two separate aircrafts will be used for seeding and cloud and environmental observations. These are termed as seeding and research aircrafts respectively.

4.2.4) Radar operations

We propose to use the polarized C band radar to (1) continuously collect information on natural cloud characteristics, (2) help direct the operations with the cloud physics aircraft, and (3) provide general information to forecast personnel. The characteristics of clouds will be monitored by radar to understand: (1) the large-scale organization of the cloud structures, (2) their frequency of occurrence and spatial distribution around the area of study, and (3) the temporal history, sizes, and intensities of individual storms and rain events.

The instruments used for measuring the various cloud microphysical parameters are (Details are given in Appendix):

- Particle measuring system (PMS)
- Forward Scattering Spectrometer Probe (FSSP: for measurements of cloud droplets between 2 – 45 µm diameters).
- PMS Passive Cavity Aerosol Spectrometer Probe (PCASP: for measurements of 0.1 to 3 µm diameter)
- PMS 2D-C optical Array Imaging Probe (for measurement of cloud and precipitation particles between 25 to 800 µm diameter)
- PMS 2D-P optical Array Imaging Probe (for measurement of cloud and precipitation particles between 0.1 to 6.4mm diameter)
- Cloud Liquid Water (CLW) sensor
- Cloud Condensation Nuclei (CCN) counter
- Condensation Nucleus (CN) counter
- Cloud seeding Material (20 hygroscopic flares)
- GPS system for location
- Temperature, pressure and dew point sensors
- Digital Video camera
- Data recording system

These instruments are important to evaluate the effects of seeding because they provide information of the background natural characteristics with which the seeding material competes. This instrument package has been designed such that all parameters related to evaluating the seeding potential for clouds could be assessed. These include instruments to assess aerosols and trace gases that contribute to the formation of droplets and ice in clouds, the microphysical instruments to assess the natural and seeded precipitation processes, and instruments to characterize the local thermodynamic structure of the atmosphere in which clouds develop.

During the experiment, it is proposed to enhance atmospheric observational network by Radiosonde soundings (twice a day) at the location and fine resolution rainfall measurements for ground validation.

4.2.5) Declaration of case

The radar operator will vector the pilot to most promising clouds. Until decision time, the radar operator and pilot may converse about the nature of situation, which cloud to choose and so on. Before launch of the aircraft, the pilot will monitor the radar displays for getting overall clouds populations.

After launch the pilot will search for the suitable cloud for seeding purpose. Then case is declared. Then decision of seeding will be taken from the randomization procedure described below.

4.2.6) Randomization procedure

The randomization will be carried out similar to South African experiment. The pilot will carry set of paired envelops for each case. The radar operator will open his envelop which will have options seed or no seed. He will communicate the result to pilot. The pilot will open his envelop which will have options yes or no. Based on that pilot will take decision for seed or not to seed. If in the first case the outcome is seed, then immediately next case, the decision will be opposite to it i.e. no seed. For the third case again randomization will be done. In this way there will be equal number of seed and no seed cases. On every day there will be equal number of seed / no seed cases so bias of synoptic situation will be removed.

4.2.7) Evaluation of the results of the experiment

The Wilcoxon-Mann-Whiteny (WMW) test will be used to test the differences between the means from two classes. WMW is non parametric test. Therefore the samples drawn need not be from a particular distribution. The sample size required for 5% error and 80% power to detect a 25% increase in rain mass due to seeding is 266 case, evenly divided between the seeded and control clouds.

4.2.8) Exploratory analysis

Measurements of various cloud properties from radar and cloud microphysics instruments will be compared for the seeded and not seeded cloud. Some of the quantities that will be examined in the exploratory phase of the analysis are:

- Cloud drop size distribution near cloud base and aloft
- Rain drop size distribution near cloud base
- Concentrations of drizzle-size drops
- Graupel embryos
- Ice formation process (ice crystal concentrations, riming rates etc)
- Duration of cloud after decision to seed
- Area-time integral
- Time history of the number of active clouds
- Precipitation measurements every 5 minutes over the lifetime of cloud
- Cloud mass measurements every 5 minutes over the lifetime of the cloud
- Cloud area measurement every 5 minutes over the lifetime of cloud
- Cloud mass measurement above 6 km every 5 minutes.
- Cumulative total of rainfall
- Updrafts / downdraft

5 Implementation of CAIPEEX

The proposed experiment is planned to carry out in two phases. Phase I is devoted for intensive cloud and aerosol observations over different parts India. In Phase II precipitation enhancement experiment would be carried out by artificially the seeding the clouds.

5.1) Phase I programme

Phase I of the CAIPEEX will be carried out during the period May through October 2008. The objectives of phase I are:

- **To measure background concentrations of aerosols and CCN during premonsoon, monsoon and post monsoon periods over the country.**

As discussed above, the seeding particles are required to be larger in size than the existing CCN for triggering rainfall mechanism. The space-time distribution of background CCN will help in designing the flares of appropriate chemical composition in the phase II programme.

- **Observations of hydrometeors in the clouds.**

The information of space-time variations of spectra of hydrometeors is very essential in isolating the marine clouds from the continental clouds. It is well known fact that marine clouds do not respond effectively to the cloud seeding, as there exists abundance of large size CCN of marine origin.

- **Cloud simulation studies by NWP models**

The cloud model studies will help to understand efficiencies of various paths leading to precipitation. Also it will enhance the understanding of the different mechanisms operating within and surrounding the cloud environment.

- **Preparation of climatology of cloud microphysical properties**

The cloud climatology and information on cloud microphysical properties will be useful in deciding the opportunity windows of cloud seeding experiments to be carried out in phase II.

- **Exploration of possibility of indigenous design of flares.**

The background CCN distribution will guide the type of flares required in the phase II experiment. If flares are produced indigenously, then choices remain open for use of appropriate type of flares.

- **Exploration of possibility of using instrumented Indian aircraft for the Phase II and polarized C band radar.**

Polarized C- band radar is of great use because it can distinguish the hydrometeors effectively. The knowledge of distribution of hydrometeors within the clouds is essential for deciding the location within the cloud for introduction of the larger size CCN for rain enhancement. Phase I is planned during the year 2008. Attempts will be made to use Indian Instrumented aircraft if possible. As discussed above, there were aerosol observations over India in the recent past using Indian Aircraft. The proposed experiment needs cloud microphysics instruments which have not been used during past experiments.

The alternative is to go for hired instrumented aircraft. This approach has many advantages. The scientists will get hands on experience of handling the instruments. This will be very crucial for procurement, calibration etc of the instruments in future for long term use in the institute. It will also provide some lead time for considering option of Indian aircraft with imported instruments.

- **Selection of sites for the second phase experiments.**

The main randomized experiment will be carried out in the Phase II programme. The information gathered in Phase I will be useful for deciding the site for the Phase II experiment.

5.2) Pilot experiment in year 2007

Before carrying out Phase I programme in the year 2008, it is proposed to carry out a pilot experiment in the monsoon season 2007. This is intended for a period of few weeks. Aerosol observations over some selected places will be taken. The objectives of the pilot experiments are:
To reconfirm our objectives proposed in the phase I.

To get familiarization and hands on experience with operating instruments.
Develop contacts with various governmental organizations for getting necessary permissions, availability of suitable air ports for aircraft landing, fueling etc.
Design the strategy for data archival and transmission to participant scientists.

The aircraft observations will be carried out over different parts of India. It is planned to have the sorties in west-east direction covering sea and land regions. Each traverse will start at location north of previous location. The beginning will be at the southern most part of India.
In addition to regular IMD upper air observations, dropsonde will be used to get atmospheric data during the sorties.

5.3) Phase II: Cloud Seeding Experiment

Based on the results of Phase I experiment, a randomized experiment will be carried out in the monsoon and post monsoon seasons of years 2009 and 2010. The experiment will use statistical methods in conjunction with numerical model simulations to evaluate the performance of the experiment. It is proposed to use a C band radar to get information regarding the distribution and intensity (radar reflectivity in terms of dBz) in a area of about 150 km radius. Two aircrafts will be used, for cloud microphysics observations and cloud seeding purposes. Hygroscopic flares with appropriate particle size distribution will be used for triggering the coalescence process in the cloud. TITAN soft were will be used for the online visualization of cloud distribution and intensity, and monitoring the seeding activity. A dense network of automatic rain guage stations will be installed in the experimental area to measure the rainfall.
Rain water samples will be collected from the seeded clouds and non seeded clouds. The chemical analysis of rain water samples will be carried out to understand any contamination of water due to seeding.

6 Participating National Institutions

CAIMPEEX is national experiment. Various national organizations will be participating in the experiment to achieve the expected goals.

IMD's existing observations will be most useful in the experiments. Data from radiosonde, pilot balloons, Doppler radars, RASS, and surface observations will be used for understanding the large scale atmospheric structure during the experiment. Special intensified rain gauge network over the seeding area will be useful for evaluating the performance of the seeding. Simultaneous data of rainfall and radar reflectivity will find useful in modifying Martial- Palmer relationship for the region.

NCMRWF's high resolution prediction of cloud amount, cloud liquid water content will be useful in decision making for the seeding. In 2003, Maharashtra cloud seeding programme, NCMRFW provided cloud forecasts for 24 and 48 hours. 24 hour forecast was found quite useful in the experiment.

The research activities of convection and cloud resolving models from IISC will be useful in understanding the convection and simulations at cloud scales.

PRL, SPL and CESS have aerosol observation programmes using ground based methods. The aircraft observations will be useful in validating the existing observations as well as calibrations of aircraft instruments.

Aerosol and cloud data will used by atmospheric science departments of Cochin, Andhra and Pune University for diagnostic studies, cloud modeling studies.

Satellite data from Indian satellite will be useful for understanding the large scale cloud structures existing on a seeding day. Aerosol observational programme under ISRO GBP will be useful in planning the CAIPEEX.

It is proposed to have collaboration with the other national experiments such as STORM and CTCZ.

It is plan to explore international collaboration for the pilot phase studies. This will help in selecting air craft, instruments, data acquisition systems etc.

7 Expected outcomes

The proposed experiment will generate a wealth of atmospheric, aerosol, cloud microphysics data which will be found useful in the research for years to come. Some of the most important outcomes are:

The hypothesis of increase on precipitation by seeding the clouds will tested. Attempts will be done to discover under what conditions and over which area, the hypothesis works well and over which area and time of year, it fails. Where it works, what should be ideal way to achieve best possible results. A guide line can be prepared to state governments interested in carrying out precipitation enhancement experiments.

There are four ingredients for improving the Numerical Weather Forecasts, viz. (1) Good model, (2) Good initial data (3) high resolution and (4) good computer power to run the high resolution model within short time. For improving the model physics, the data in the proposed experiment will be used to validate the convection schemes and cloud schemes.

Goswami et al (2006) showed an increasing trend in the extreme rain events over India. The dynamical features of Mumbai heavy rainfall have been studied by Vaidya and Kulkarni (2007). Most of these exceptional heavy rainfall events are found to occur during the period when break is ending and active spell is to beginning. During the break conditions, level of aerosol concentrations in the atmosphere goes high because of the dry soil and prevailing large scale subsidence. Naturally the clouds formed during these periods will large number of small size particles. Microphysical processes which lead to heavy precipitation is not clearly understood and it is itself a scientific problem which needs to be addressed. The aerosol and radiation data from the proposed experiment will throw light on some the possible causes of such events.

Experience and data collected will find useful in other national experiments such as STORM, CTCZ and FDP etc.

Other possible side benefits of the proposed program will be:

- Air Pollution Assessment and associated impacts over India (health, visibility, climate)

- Hydrology Studies
- Water resources
- Enhancing research infrastructure (human resources and technology)

Enhancing the scope and utility of existing studies. The radar data from operational seeding experiments of Maharashtra, Andhra Pradesh and Karnataka are being analyzed for understanding the cloud variability over the regions. Another study being carried out is the estimation of cloud properties using satellite data. These existing studies will be strengthened through the proposed experiment.

8 Bar chart of the Implementation Plan

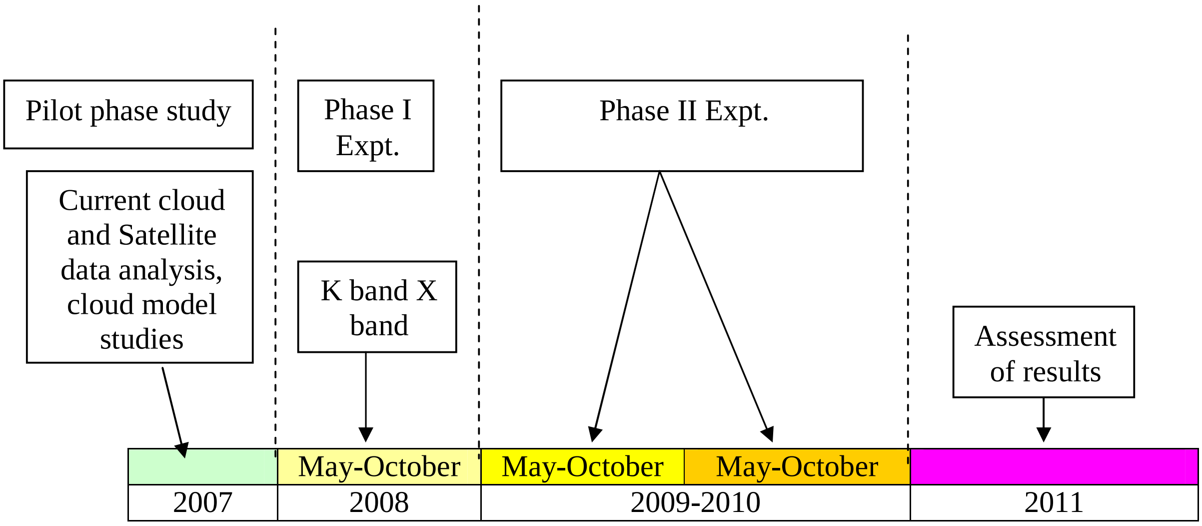

Figure 8.1 Bar chart of schedule of CAPEEX

The details of air craft instruments, aircrafts, flares, are given in the Appendix.

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Appendix

1 Aircraft Instrumentation for Cloud Studies

The seeding aircraft will be equipped with an on-board instrumentation system including a telemetry link to the operations base. The system will record time in UTC, GPS position and state variables (pressure, temp.). Forward-looking video will record flight conditions. The cloud physics/seeding aircraft will carry an instrumentation package to conduct the physical measurements as part of the randomized experiment and cloud conditions when no suitable clouds are available for the seeding. The aircraft will be fitted with following instruments

VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION	FREQUENCY
Air temperature	Rosemount 102DB1CB	-50°C to +50°C	0.1°C	0.01°C	1 Hz
Air temperature (reverse flow)	0.038" DIA. Bead Thermistor	-30°C to +50°C	0.05°C/0.3°C incl DHC	0.01°C	< 1 s TC
Relative humidity (reverse flow)	Thermoset Polymer RH Sensor	0 to 100% RH	2% RH	0.1% RH	5 s TC @ 20°C
Barometric pressure	MEMS Pressure Sensor	0 to 110000 Pa	100 Pa	10 Pa	20 Hz
u wind component (+ North)	Extended Kalman Filter (EKF)		0.50 m/s @ 75 m/s TAS	0.01 m/s	5 Hz
v wind component (+ East)	Extended Kalman Filter (EKF)		0.50 m/s @ 75 m/s TAS	0.01 m/s	5 Hz
w wind component (+ Down)	Extended Kalman Filter (EKF)		0.50 m/s @ 75 m/s TAS	0.01 m/s	5 Hz

Position (Latitude/Longitude)	WAAS DGPS		2 m (2 □)	< 1 m	5 Hz
Altitude	WAAS DGPS	-300 to 18000 m	5 m (2 □)	< 1 m	5 Hz
Geometric Altitude	King KRA 405 Radar Altimeter	0 to 2000 ft	3% < 500 ft 5% > 500 ft	0.48 ft (0.15 m)	
Roll Attitude (°)	MEMS IMU/GPS/EKF	-60 to +60°	0.1°	0.01°	5 Hz
Pitch Attitude (°)	MEMS IMU/GPS/EKF	-60 to +60°	0.2°	0.01°	5 Hz
Yaw Attitude (°)/ Heading	MEMS IMU/GPS/EKF	0 to 360°	0.1°	0.01°	5 Hz

Angle of attack (°)	MEMS Pressure Sensor	-15 to +15°	0.03° @ 150 m/s	0.001° @ 150 m/s	20 Hz
Side-slip (°)	MEMS Pressure Sensor	-15 to +15°	0.03° @ 150 m/s	0.001° @ 150 m/s	20 Hz
True Air Speed	MEMS Pressure Sensor	0 to 150 m/s	0.1 m/s	0.01 m/s	20 Hz
Video record	Sony DCR-DVD 201				
Logging, telemetry & event markers	ESD DTS (GPS)				1 Hz

Cloud droplet spectra	DMT CDP	2 to 50 µm		1 to 2 µm, 30 bins	1 Hz
Cloud particle spectra	DMT CIP	25 to 1550 µm		25 µm, 62 bins	1 Hz
Cloud particle image	DMT CIP	25 to 1550 µm		25 µm	
Liquid water content	DMT LWC-100	0 to 3 g/m^3	0.05 g/m^3	0.01 g/m^3	1 Hz
	CDP calculated	> 3 g/m^3			1 Hz
Isokinetic aerosol inlet	Brechtel double diffuser inlet	28 lpm			100 m/s
Aerosol spectrometer	PMS PCASP SPP-200	0.1 to 3 µm		0.02 µm, 30 bins	1 Hz
CCN	DMT CCN counter	0.5 to 10 µm 0.1 to 1.2 % SS	see text	0.5 µm, 20 bins	1 Hz

2. Aerosol/Radiation Instruments

Microwave radiometric profiler

The microwave radiometer profiler provides vertical profiles of temperature, humidity and cloud liquid water content as a function of height or pressure at approximately 5-minute intervals for nearly all weather conditions. The profiles are derived from measurements of absolute microwave radiances (expressed as "brightness temperatures") obtained at twelve frequencies in the range of 22-30 Ghz and 51-59 Ghz. The data are useful for input to numerical weather forecast models and others that require continuous, high temporal resolution profiles. The microwave radiance measurements are useful for testing models of microwave radiation transfer used to derive the profiles.

Upwelling and downwelling shortwave irradiance

Kipp & Zonen CM22 Pyranometer

Upwelling and downwelling longwave irradiance

Kipp & Zonen CG4 Pyrgeometer

CR10X Datalogger

Three-wavelength integrating Nephelometer

Integrating nephelometers are unique analytical instruments useful for short- or long-term measurements of the light-scattering coefficient of atmospheric aerosols. It allows to measure both total and backscatter signals. This instrument will allow us to estimate single scattering albedo of aerosols (fraction of absorption in the total extinction), which is one of the important parameter for radiative forcing estimates.

Black carbon measurements

The *Aethalometer* is an instrument that measures suspended carbonaceous particulates, an important species of air pollutant. Aerosol Black Carbon ("BC", or "EC" for Elemental Carbon) is a ubiquitous component of combustion emissions. It is most obvious in diesel exhaust, but it is emitted from all combustion sources together with other species such as toxic and carcinogenic organic compounds, and it can be found everywhere. *Aethalometer* uses a continuous filtration and optical transmission technique to measure the concentration of BC in near-real-time.

Single Particle Soot Photometer (SP2)

It is based on Nd:YAG intracavity laser induced particle incandescence. Direct measurement of black carbon mass, spherical equivalent diameter derived from mass. Suitable for airborne mounting in the aircraft cabin.

Multiparameter Raman Lidar system for vertical profiling of temperature and water vapor.

3 Flares

In the present approach, pyrotechnic flares (figure 9.1) are used for seeding purposes. There are two types of flares: Hygroscopic and Glaciogenic.

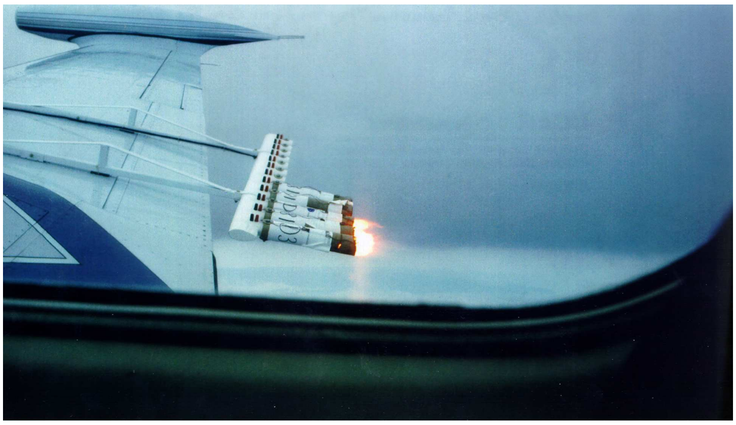


Figure 9.1. Hygroscopic flare

Each Hygroscopic flare contains 1 kg of sodium chloride. These flares produce small salt particles of the uniform size of 0.5 micrometer. These flares are fitted in the racks attached to the wings of the aircraft. These are used for warm cloud seeding method. The warm clouds are those whose tops lie below the zero degree isotherm. The flares are used for seeding in the updraft areas below the base of convective clouds. The hygroscopic seeding broadens cloud droplet spectrum and accelerates the coalescence process.

The glaciogenic flares contain silver iodide as the seeding material. They are of two types viz. Ejectable and BIP (burn in place) having masses 20 and 150 gms respectively. The BIP flares of are fitted in the racks attached to the wings. These are fired in the middle part of the cloud in the updraft region. Ejectable flares are fitted in the box at the bottom of the plane. These are fired from the top of the cloud.

There are significant operational advantages to this form of seeding. The amount of the material required is less; seeding particles are of required uniform size. The target area for the seeding can be identified precisely and equally seeded precisely.

The majority of the hygroscopic cloud seeding flares currently in use are based on the formula of Hindman (1978) that was developed to initiate fog for cover of military vessels over the sea. The pyrotechnic flare was composed of 18% hydrocarbon binder, 5% magnesium, 10% sodium chloride, 65% potassium perchlorate and 2% lithium carbonate. The flares were cast in beer-can size cardboard container (12 cm long 7 cm diameter) and weighed 454 g each. The linear burning rate of the flare was 0.66 mm per second.

The chemical combustion reactions in the flare were

$$KCLO_4 \longrightarrow KCL + 2O_2$$

$$NaCl \longrightarrow NaCl$$

$$Li_2CO_3 \text{-------}\rightarrow Li_2O + CO_2$$

$$Li_2O + H_2O \text{------}\rightarrow 2LiOH$$

$$2LiOH + CO_2 \text{--------}\rightarrow Li_2CO_3 + H_2O$$

$$2Mg + O_2 \text{-------}\rightarrow 2MgO$$

$$(CH_2)_n + (O_2)_n \text{------}\rightarrow NCO_2 + NH_2O$$

After combustion, the composition of the effluent was

- 35% KCL
- 10% NaCl
- 0.7% Li_2CO_3
- 8.3% MgO and
- 46% gaseous products.

An examination of electron micrographs of seeding particles captured on glass slides suggest that the salt particles produced in the burning of flares nucleate on the MgO produced in the combustion of the flare. The combustion temperature of the flare is unknown, but is most likely in the excess of 2000^0 C. Under these conditions, the salt will volatilize and then re-condense rapidly, forming small particles. There is no clear cut information regarding how the formation of large particles depend upon the temperature.

In the NERP (National Precipitation Research Program S. A.) the size distribution of the particles from the seeding flares was measured. The measurement were made using a passive cavity aerosol spectrometer probe (PCASP) and a forward scattering spectrometer probe (FSSP) both manufactured by Particle Measuring Systems Inc.

For these measurements, the instrumented Learjet of South Africa was flown behind the seeding aircraft. It was observed that the particles have log normal distribution. The majority of the particles were in the 0.2 0.4 micro meter range.

A recent model study by Cooper et al (1997) gives good insights into the theory behind hygroscopic cloud seeding and provides guidance on the necessary steps to optimize the cloud seeding flares.

- If the CCN that are introduced into the cloud from seeding flare are larger in size than the natural CCN, the introduced CCN will activate preferentially over the natural CCN and change the character of the drop size distribution to favor coalescence and formation of rain.
- The most important contribution to the seeding effect arises from the particles in the size range from 1 to 10 micro meter range.

The conversion to the precipitation was fastest for concentrations of the seeding material from 50 to 200 cm^{-3}. For above and below of this concentration, the conversion rate is slower.

4 View of Instrumented Aircraft

Figures 9.2 and 9.3 present view of the instrumented aircraft and cloud physics instruments (from Bruintges Personal communication)

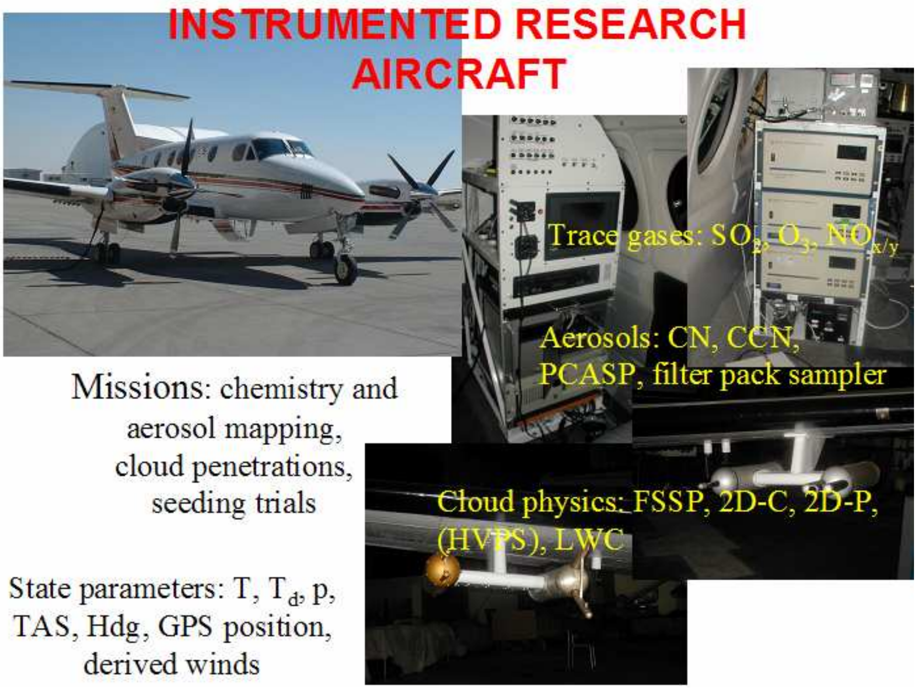


Figure 9.2 View of the instrumented aircraft (from Bruintges Personal communication)

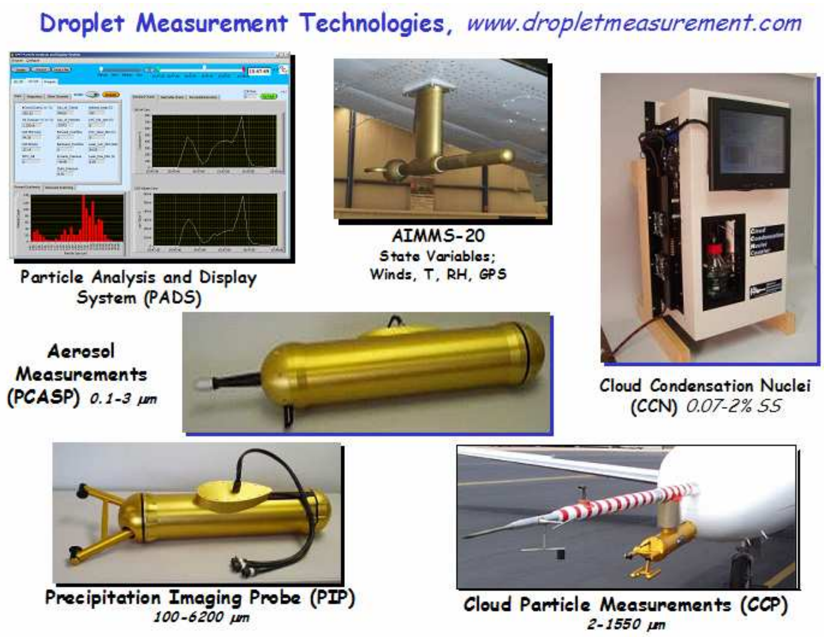


Figure 9.3 View of Cloud Microphysics instruments (from Bruintges Personal communication

The most commonly cloud physics instruments used are described briefly below.

1. Cloud Liquid Water Measurement System (LWC 100)

The LWC100 cloud liquid water measurement system consists of the control unit, the power supply, and a sensor head (shown here). The sensor head holds the wire-wound element between two prongs that position it three inches away from the outside aircraft skin. The sensing element, in conjunction with a remotely mounted power supply, is interfaced with the display module. The display is mounted within the data acquisition system and is interfaced with the computer for recording and displaying liquid water content measurements.

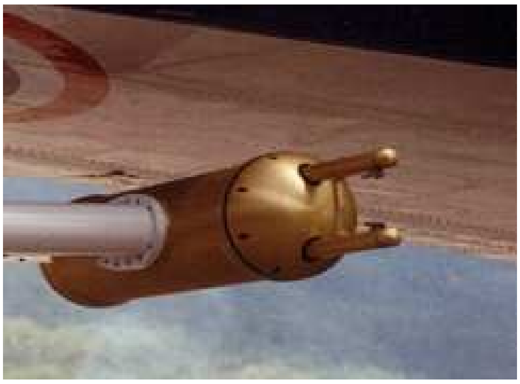
2. **Total Temperature Sensor (RT105)**

The RT105 is a de-iced platinum resistance-type total temperature sensor for high performance aircraft applications where accurate total temperature measurements are required. The sensing element is protected from small foreign particles such as sand, ice and insects. The sensor features a de-icing heater that dissipates 270 watts under in-flight conditions with 28 volts DC applied. The RT105 is interfaced with the data acquisition system and accurately measures and displays temperatures from -50°C to +50°C.

3. **Dew Point Temperature Sensor**

The Dew Point Sensor is a complete optical dew point system for monitoring in-flight atmospheric dew and frost points. It is the only aircraft instrument that provides two stages of thermoelectric cooling. It can reach frost points between –60°C and -70°C, depending on mounting configuration and operating conditions. No auxiliary coolants are required. Included in the system are a water-excluding inlet probe and a pressure tap for monitoring static pressure. A digital display with resolution to 0.1°C is provided as well as an analog D.C. voltage output that is interfaced with the data acquisition system for display and recording purposes.

4. **Cloud Particle Probe**



Study of complete microphysics requires knowledge of the sizes, number, and shapes of the hydrometeors (water and ice particles) within the cloud. This probe does exactly that. A laser shines from one "arm" of the probe onto a row of photo detectors in the other. When any particle passes between the arms, it shadows the detectors, and high-speed processing records which of the 32-element detector array were shadowed, and in which order. The image shape can then be accurately reconstructed, and the maximum dimension determined.

The 2D2-C two-dimensional optical array probe (OAP) stores complete two-dimensional images of encountered particles for shape analysis in addition to one-dimensional sizing.

5) Precipitation Probe

This probe complements the Cloud Particle Probe, Cloud microphysics studies requires knowledge of sizes, number, and shapes of larger hydrometeors within and beneath the cloud. A laser shines from one "arm" of the probe onto a row of photo detectors in the other. Physical measurement principles are the same. The arms are spread to increase the depth of field, and allow a larger sampling volume to ensure representative measurement of the larger, but fewer, precipitation-sized particles. The image shapes are reconstructed, and the maximum dimensions determined. The number of particles of each size and shape are also tabulated.

The 2D2-P Precipitation Probe is an aircraft-borne instrument that utilizes photo diode array and photo detection electronics.

5 Cloud Droplet Spectrometer Probe (FSSP 100)

The Foreward-Scattering Spectrometer Probe or FSSP, is used to measure the sizes and numbers of cloud droplets. This instrument focuses specifically on these very small droplets, and does not measure larger (precipitation-sized) drops, or ice particles. The primary purpose of this instrument is to determine in real-time the character of the sampled clouds, that is, whether they be maritime or continental.

The FSSP-100 is a one-dimensional laser probe that provides sizing of particles up to 45 microns diameter. The probe outputs a parallel digital size code along with a strobe pulse for each acceptable particle encountered. The output is interfaced with the data acquisition system for collecting, displaying and recording the data provided. The available ranges of the FSSP-100 are controlled by the data acquisition system.

5. Instantaneous Vertical Speed Indicator or Linear Acceleration

An aircraft configured for level flight will climb or descend only as the air through which it is flying rises or falls. In studying clouds, we take advantage of this fact by flying cloud penetrations with the aircraft at constant attitude. The pilot does not worry about maintaining constant altitude, but rather allows the aircraft’s motion to be sensed and recorded, thus providing a measure of cloud up- and downdrafts. Updrafts are particularly important, for they mark the location of the developing cloud volume, produce additional cloud condensate, and are often used to transport seeding agent upward into cloud when treatment is done from cloud base. The BV4.0 is an electric instantaneous rate of climb indicator that features smooth action, rapid response rate with high accuracy.

6 Specifications of Radars to be procured in IITM

6.1) Specifications for the Mobile Dual Polarized Ka-band Doppler Radar

Frequency Range	33-37 GHz (Ka Band)
Transmitter Type	Extended Interactive Klystron/TWT based
Minimum measuring range	100 m
Maximum measuring range	18 km
Range resolution	100 m
Sensitivity	- 45 dBz at 5 km
Transmitter Polarization	Both co- and cross-polarization
Receiver polarization	Both
Pulse repetition frequency	2-10 kHz
Beam width	0.5°
Antenna	Steerable Parabolic Antenna with Radome
Azimuth steering	360° with ±1° accuracy and 0-4 rpm
Vertical Steering	-2° to +92° with ±1° accuracy
Doppler processing	Pulse Pair and FFT
Antenna mounting	Trailor-mountable
Container	Shelter for radar system, tower, radar operator, air conditioner etc.
Software	Custom-built licensed software with all inbuilt algorithms for cloud physics studies Source code to be supplied
Computer and control	Industrial workstations for operation and control of the radar
Power	230 V, 50 cycles/s single phase
Calibration	BITE and Self calibration
Side lobe for cross polarized levels	Both -25 dB or better
Polarimetric output	Z_{DR}, K_{DP}, ρ_{HV}, Z, V, σ, ϕ_{DP}
Training and Installation	Onsite training and Installation

6.2) Specifications for the Mobile Dual Polarized X-band Doppler Radar

Frequency Range	9.3 – 9.6 GHz (X-Band)
Minimum measuring range	1 km
Maximum measuring range	80 km
Range resolution	1 km
Sensitivity	0 dBz at 10 km
Polarization	Both co- and cross-polarization
Receiver polarization	Both
Pulse repetition frequency	2-10 kHz
Beam width	1°
Antenna	Steerable Parabolic Antenna with Radome
Azimuth steering	360° with ±1° accuracy and 0-4 rpm
Vertical Steering	-2° to +92° with ±1° accuracy
Doppler processing	Pulse Pair and FFT
Antenna mounting	Trailor-mountable
Container	Shelter for radar system, tower, radar operator, air conditioner etc.
Software	Custom-built licensed software with all inbuilt algorithms. Software source code to be supplied
Computer and control	Industrial workstations for operation and control of the radar
Power	230 V, 50 cycles/s, single phase
Calibration	BITE and self calibration
Side lobe for cross polarized levels	Both -25 dB or better
Polarimetric outputs	Z_{DR}, K_{DP}, ρ_{HV}, Z, V, σ, ϕ_{DP}
Training and Installation	Onsite training and Installation

6.3) Specifications of Micro Rain Radar (MRR) :

Transmit frequency	24.1 GHz
Transmit power	50mW
Receiver-Transmitter Antenna	offset -parabolic, 0.6 m diameter
Beam Width (1-way, 3 dB)	2°
Modulation	FMCW
Height resolution	35 ... 200 m
Averaging time	10 ... 3600 s
Height range	29 range gates from 2 x range resolution to 30 x range resolution
Measured variables	average power spectra of the receiving signal with 2048 lines resolution
Interface	RS232 9600 ... 57600 Baud
Power supply	24 VDC / 25 W
Weight	12 kg
Dimensions	0.6 m x 0.6 m x 0.6 m