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A survey and assessment of the design and evaluation techniques of cumulus cloud modification experiments for rain enhancement

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Abstract

Physical basis of cloud seeding and meteorological considerations involved in the efficient design of experiments for rain enhancement are discussed. An analysis of the various designs and statistical techniques currently being employed for evaluating the experiments is presented. The limitations of available statistical methods, when used alone, to establish significantly the changes in rainfall caused by cloud seeding within a reasonable period of experimentation are brought out. The manner in which remarkable increase is produced in the power efficiency of some tests when applied along with the simultaneous measurements of physical covariates or predictor variables and proper stratification of data is elucidated. The scope of anlayses based on postfactum stratifications or partitioning of data and the problems of multiplicity of analyses are discussed.

Key words : Cumulus cloud modification, rain enhancement experiment, statistical design and evaluation.

1. Introduction

There is an impending global energy and water shortage crisis. Considerable effort is therefore presently being made to tap the abundantly available atmospheric resources like sunshine, wind and precipitation to mitigate the shortages. These energy sources are renewable and so are perennial components of a country's natural resources.

Most of the world's rainfall is produced by cumulus clouds and convective systems[1–3]. The region of the southwest monsoon season trough over India and the neighbouring areas has been identified as the area where convective instability is present within deep layers and up to greater heights than elsewhere[4]. The controlled and systematic modification of these clouds to yield more rain could be a very valuable method for atmospheric resource enhancement. It holds enormous potential benefit for drought relief, water management, increased food poduction, more effective power generation and utilization[5–8]. Cumulus cloud modification experimentation is therefore one of the most challenging and fruitful opportunities ever offered to the meteorologists to serve society.

Experiments are in progress in India, as in other parts of the world, from fifties, to study the feasibility of rain enhancement from cumulus clouds. Weather modification experiments are merely not of academic interest today; both Government and society are keenly awaiting the successful culmination of these experiments to mitigate the impending chronic water shortages[9-10]. It looks surprising that in spite of tremendous efforts of world scientists in the field, backed by modern technology, very few experiments have successfully demonstrated the capability of rain enhancement. This is mainly because it is expensive, difficult and time consuming to scientifically establish a cloud modification hypothesis than to apply it operationally.

High natural variability in both space and time of rainfall from cumulus clouds, coupled with large inaccuracies in rainfall measuremcts, has been the basic difficulty in evaluating a treatment effect on these clouds. Natural rainfall, within a few hours duration, has been observed to commonly vary by factors of $\sim$ 10–10^3, from fraction of a millimetre to several centimeters, while the largest seeding effects have rarely exceeded a factor of 3; often a demonstrated increase of 10% would be of priceless value[1]. Scientists have recognised the basic fact that a cumulus cloud can do virtually anything all by itself in the natural process; without any sort of intervention, a field of identical looking clouds can either rain copiously or vanish quietly. The crux of the problem is to estimate what the cloud system would have done had the seeding treatment not been applied.

Despite major problems involved in the field of rain enhancement, remarkable progress has been made during the last few years in cumulus modification. An analysis of the developments in the statistical design and evaluation techniques of randomized cumulus modification experiments, culminating in a synthesis of increased physical understanding and more accurate simulation of cloud processes, advances in accurate *in situ* and remote measurement of cloud physical parameters and rainfall at the ground with wide repertory of classical and Bayesian statistical tools, is presented.

2. Physical basis of cloud seeding

Cloud systems are very complicated and involve processes on several size scales, ranging from cloud microphysics to large-scale interactions of convective cloud populations, spanning through several orders of magnitude. Many different responses and outcomes to the same modification treatment can therefore follow depending upon the initial conditions of the cloud environment systems.

The total rainfall over an area is strongly influenced by moisture supply, atmospheric stability, topographic features and the large scale wind fields. The growing cumulus clouds interact with one another and with their environment including topographic features. There appear to be therefore manifold possibilities of modification of cloud processes by man, either deliberately or inadvertently.

2.1. *Modification hypotheses*

Enormous amount of energy is expended in natural atmospheric processes. Scientists have been searching for weak points in the cloud systems where energetically small trigger would produce sizable reaction. A few processes have been found that occur at critical points in the transfer mechanism and which present unique opportunities to influence energy transfer in significant ways. As stated by Braham[11], theories of cloud response to seeding are simplistic and inadequate. Much of the existing knowledge about precipitation and ways in which clouds are affected by seeding has come from experiments in which cloud seeding was coupled with detailed study of associated physical and dynamical processes in the prevailing clouds. The most plausible hypotheses for rainfall enhancement by seeding of cumulus clouds based on current scientific understanding and intuition are described. Conclusions regarding the physical mechanisms involved are tentative and need to be firmly established by detailed measurements and experimentation.

The failure to recognise the dominant mechanism and the time and space slot during which it is most effective, in the cloud life span, may result in the use of wrong seeding technique, producing negative or no effect on the rainfall. Basic research must therefore precede any seeding effort to determine the most effective 'static' or 'dynamic' technique applicable to the clouds under the environmental conditions prevailing in the area[12,13].

2.1.1. *Warm cloud seeding hypothesis*

Gravitational instability of cloud particles, which is manifested in rainfall, can be better exploited in the case of those clouds whose tops do not reach above the freezing (0° C) level. Such clouds are called warm clouds and rain is produced by the rapid growth of cloud particles by collision-coalescence mechanism. Here large drops must exceed a critical size before the process can proceed at any significant rate. It has been observed[14, 15] that a broad spectrum of drop sizes, with some drops larger than 25 micron radius, is necessary for drops to grow fast by collision-coalescence process and produce rain. Computations made by Bartlett[16] and Berry[17] have shown that distributions having more larger droplets develop faster than those having fewer larger droplets. The development of large drops by condensation depends on the existence in sufficient numbers of giant nuclei greater than one micron in radius. The fact that clouds exist so frequently without producing rain is evidence that very often condensation does not produce larger drops[18–20].

Warm cloud seeding hypothesis is based on the premise that, seeding of clouds with giant hygroscopic nuclei or with water spray will enhance the collision and coalescence of existing droplets sufficiently, to lead to precipitation in a cloud which would otherwise produce no precipitation or produce precipitation belatedly.

2.1.2. *Cold cloud seeding hypothesis*

Phase instability of water in the supercooled state is exploited in the modification of clouds whose tops reach above the freezing level. Such clouds are called cold clouds. The dominant mechanism producing precipitation in cold clouds is the three phase or Bergeron-Findeisen process. It has been found that cloud drops remain liquid even at sub-zero temperatures and ice crystals, when they form, are much fewer in number than the liquid droplets[21]. As the saturation vapour pressure over ice is less than that over water, the cloud droplets evaporate and the ice crystals grow rapidly. Since ice crystals are much fewer in number, they become much larger than the pre-existing drops. These crystals then fall relative to the remaining small droplets and collect them. The two processes described above are complementary. The phase change may initiate collision and coalescence mechanism and lead to the rapid formation of precipitation in mixed phase clouds. In cold clouds both ice crystal growth and the collision-coalescence mechanism are in competition, and the rain may be produced either way. Which process dominates in a particular situation depends primarily on the temperature at cloud top, the cloud liquid water content and water drop spectrum[22].

Cold cloud seeding hypothesis is based on the premise that crystallization of supercooled drops can be stimulated at the lower elevations of clouds with warmer temperatures by seeding with artificial freezing nuclei such as fine silver iodide particles. The rationale behind this idea is that, ice crystals formed at warmer temperatures, where naturally active nuclei are not available, will have extended growth conditions to develop into large ice crystals. Once large ice crystals are formed, Bergeron-Findeisen mechanism efficiently comes into play and helps in rapid growth of ice crystals at the expense of water and subsequent production of precipitation.

2.1.3. *Static and dynamic cloud modification*

Both the above seeding hypotheses visualize altering just the size spectrum of the cloud particles or its microphysics and thus attempt to increase only precipitation efficiency of these clouds. This concept, based on precipitation efficiency, is the static seeding approach and rainfall enhancement of the order of 20% can be expected with this method.

Several numerical cloud models have been developed to simulate the microphysical processes and their interaction with cloud dynamics[23, 24]. It is found that interactions between microphysical processes and cloud dynamics are decisive only in the marginal situations and cloud dynamics has a predominant control on cumulus precipitation than its microphysics. Earlier, Battan[25] and Braham[26, 27] had also arrived at the same conclusion for clouds in Missouri (Project Whitetop) and Arizona regions, that, it is the regional dynamics of the atmosphere, not the microphysical processes, which control the precipitation for these clouds. However, Langmuir's[12] idea of invigorating cloud updrafts to increase the vertical development of the supercooled clouds, by artificially freezing rapidly the available water content and thereby increasing the cloud buoyancy by the influx of released latent heat, was tested for the first time in Australia by Kraus and Squires[28]. The concept has been subsequently utilized in several experiments to obtain more rainfall through the so-called 'dynamic effect' produced by seeding of individual clouds[29-33].

The results of these experiments have been a mixed success[11]. Only in the Florida area, it has been demonstrated without doubt that, large increases of rainfall can be obtained from 'dynamic seeding' of individual clouds. The scope of Florida Area Cumulus Experiments was therefore enlarged to determine whether rainfall over a mesoscale area (~ 1·3 × 10^4 km^2) could be increased by 'dynamic seeding'. Results of the experiments conducted during 1970–75 are inconclusive. It is thought that possible increases in rainfall over the target area on days with moving radar echoes were more than offset by decreases on days with stationary echoes[34, 35]. However, the results for late 1975 and 1976 with new pyrotechnics show[35] overall increase of about 70%.

The dynamic seeding concept has its physical basis in the observations that newly risen cumulus towers produced by active updrafts consist almost entirely of water drops even at sub-freezing temperatures around − 10° C[36, 37]. Provided updraft core regions are quickly and accurately seeded with large number of freezing nuclei (100–1000 per litre) to produce sudden glaciation of supercooled water and infusion of latent heat released into the core, fresh buoyancy is generated and the updraft gets invigorated. This increases the growth and life of the cloud to process more water and thus produce more rain. The whole effort is directed at producing microphysical effects to improve the efficiency of internal microphysical processes. This leads to optimization of interaction between microphysical and dynamical processes during cloud evolution and in generating dynamical effects to invigorate the cloud and prolong its lifetime. Large precipitation increases are thus possible due to better organisation and longer linkage of the updraft with the low-level moisture field.

It is often wrongly emphasized that 'massive seeding' is necessary for producing dynamical effects in convective clouds. This concept has arisen in the context of Florida Area Cumulus Experiment (FACE) where only a narrow time 'window' is found to exist for effective dynamic seeding before natural glaciation becomes predominant. The whole reaction has to be very rapid and explosive to be effective in the Florida area and therefore 'massive seeding' is required[34]. Experiments have been reported where dynamic effects were produced in convective clouds by seeding with moderate quantities of dry ice or silver iodide 120 to 700 gm per cloud[30, 38, 70]. From observations made in summer cumulus clouds in southern Missouri (USA), Koenig[39] found that rapid natural glaciation takes place in clouds at freezing levels once large liquid drops (~ 250 μm) are formed in sufficient numbers (~ 100 per m^3). Thus, it seems that dynamic effect could be produced by warm seeding of the clouds to artificially produce large liquid hydrometeors in the earlier evolutionary stage of mixed phase clouds[40, 41]. The importance of the early freezing of rain water at temperatures around − 5° C in producing dynamic growth has been theoretically demonstrated by Orville and Hubbard[42]. Various hypotheses regarding dynamic seeding therefore really need testing by undertaking detailed studies of cloud microphysical, dynamical and environmental conditions and their mutual interaction in different areas. Transfer of seeding techniques and technology from one area to another without careful study and detailed specification of all relevant factors are to be deprecated.

3. Characteristic features of convective rainfall

One of the main obstacles in the way of conclusively establishing marginal increases in rainfall resulting from cloud seeding experiments is the high natural variability of convective rainfall and its accurate measurements. Changnon and Huff[43] have investigated the critical effect of rainfall variability upon the verification of cloud seeding experiments with two concentrated networks for raingauges, for convective rainfall over the Illinois region (USA) for periods of five to ten years. They have suggested that the results should be applicable to other areas of similar topography and rainfall characteristics. Schickedanz and Huff[44] have given the problem extensive treatment for rainfall over the same region. However, the authors have ignored the effect of measurement errors in their simulation experiments to test various statistical designs for detecting modest (10-20%) increase in areal rainfall.

A unique study at great cost and labour has been done[45] using highly accurate measurements from a dense raingauge network (3 km^2/gauge) over a mesoscale area ($\sim$ 600 km^2) near Florida (USA). Salient features of their results, which depict typical characteristics of the summer convective rainfall observed in several parts of the world, are reproduced below to highlight the formidable nature of the problem.

The daily rainfall patterns show extraordinary gradients ; while the maximum rain gradient record was 94 mm in 1 km in one part, there are several areas in this small network where there was nearly no rain. The point 24-hour rainfalls decrease to one-half the core maximum in about 3 km. The mean rain gradient within the first 3 km of the rain maximum is 7·1 mm/km.

Nearly 50% of the total rainfall was measured on 15% of the days with rain. About 50% of the rain falls in 10% of the time with rain. In the mean for all days with rain. 50% of the rain volume is contained within about 17% of the area with rain.

4. Rainfall measurement accuracy *vs* raingauge density requirements

Accurate areal rainfall measurements require raingauge observations on spatial scales commensurate with rainfall variability. A number of investigations have been conducted to determine the range of accuracy of raingauge networks of different densities in the measurement of convective rainfall[46-48]. The most comprehensive analysis is provided by Huff[48] in his review paper.

The problem of accurate rain measurements is basically linked with its detection by the raingauge network. Rain must be detected before it can be measured. For the detection of 90% of 24-hour rainfall of the order of 1 mm, it is necessary to have a raingauge density of about 65 km^2 per gauge. For the measurement of rainfall greater than 0·25 mm within a factor of two of the standard network (2·6 km^2 per gauge) 99% of the time, a raingauge density of 13 km^2 per gauge is required[45]. Since surface rainfall data are mostly being used for verification of cloud modification experiments, it is important to bear in mind that the accuracy of areal mean rainfall measurement is a function of raingauge density and the true area mean rainfall. Huff[48] has shown that for convective rainfall area mean gauge rainfall measurements are accurate to within 5% for raingauge densities > 1 gauge per 50 km^2 and for rainfall rates > 10 mm/hr. Further, area mean rainfall measurements are accurate to within 10% for gauge densities > 1 per 160 km^2 and for rainfall rates around 4 mm/hr. Network with sparse raingauge densities may not even be adequate to detect small rainfalls. A few raingauges may although give an unbiased estimate of the mean rainfall over an area, yet the sampling error or variance may be very large.

For the evaluation of areal rainfall data from cloud seeding experiments, it is useful if we know the amount of error involved in rain measurement with networks of different gauge densities and how these errors are distributed over the experimental area. For this purpose, concept of measurement error distribution has been introduced with the assumption that these errors are multiplicative[49]. On this basis, a method of estimating the errors arising out of the use of sparse rainguage network and the optimum network required for accurate measurements has been evolved. Zawadzki[50] has derived analytical expressions for the determination of statistical parameters of the spatial distribution of rainfall, which would provide estimate of error in networks of uniformly spaced raingauges, fluctuations of the estimates, and variance of the area averaged rainfall.

Of utmost importance, though often ignored to the detriment of experiments, is the problem of timely and accurate recording of raingauge data. A dedicated and conscientious service from the observers is essential to achieve the designed accuracy from the raingauge networks. Often, data are incomplete and much effort is wasted in 'cleaning and drying' of data, to eliminate errors and spurious measurements, before processing.

The problem of accurate quantitative prediction of the intensity, duration and distribution of rainfall from selected field of clouds does not appear likely to be solved in the near future. The results of cloud seeding experiments have necessarily to be evaluated by statistical methods utilizing rainfall data from seeded control events, under similar meteorological conditions. Therefore, wherever a precipitation enhancement project is planned, a good rainfall record of the past decade or still earlier periods should be considered an essential preliminary requirement and the optimum raingauge network should be established at the earliest.

5. Radar rainfall measurement—accuracy *vs* raingauge networks

Even though raingauges give accurate point rainfall measurements, errors in area rainfall measurements arise because distances between gauges are much larger than the characteristic scales of convective rain cells. Raingauge networks of high density required for cloud modification experiments are very difficult to properly maintain from the points of view of cost, maintenance, data collection, and data processing. A radar with capability to detect all the rainfall within its range, over large area ($\sim 70{,}000$ km^2), and to provide continuous measurements of rainfall with high spatial and temporal resolution for real time processing at one location, appears to be a near perfect tool for recording highly variable convective rainfall. Unfortunately, there are several inherent errors in radar measurement process, such as calibration error, large variations in radar reflectivity and rainfall rate ($Z - R$) relationship from storm to storm and within storm, radar signal attenuation by precipitation, anomalous wave propagation, inadequate beam filling by the hydrometeors and evaporation below the radar beam, radar beam blocking due to obstacles and ground clutter, etc[51-53]. Great technological advancements have taken place in radar calibration and digital recording and processing of the data with high resolution and accuracy. Inherent complexities and errors in the radar method are still the major obstacles in the regular use of radar[54-56].

Large discrepancies have been observed in the radar measured rainfall in comparison to high density standard raingauge networks. Attempts have been made to obtain higher accuracy by combining the spatial capability of radars with the point accuracy of raingauges, by automatically calibrating the radar with *in situ* measurements from a few dense raingauge clusters. Detailed studies have shown that the gauge-adjusted radar is far superior to gauges alone and provides approximate gauge density equivalence of ~ 25 km^2/gauge[54-60]. However, for high accuracy rainfall measurements (errors $\lesssim 20\%$) required for cloud modification experiments the utility of radar is limited, since the raingauges required for calibration are themselves sufficient to give the desired accuracy[54,55].

6. Experimental design—physical and meteorological considerations

The basic purpose of experimental design is to use the investigator's knowledge of the experimental material to increase the precision of the experiment with randomization to avoid bias in the results. Experimental design and statistical evaluation procedure are two logical requirements of the process of acquiring knowledge about natural processes through experimentation. The essence of a good design is, therefore, to provide from the evaluation the greatest likelihood of definite and unambiguous answers set in the modification hypothesis.

It is imperative that while designing cloud seeding experiments, optimum raingauge network over the experimental area must be utilised, if it is to be ensured that differences in seeded and control rainfall are real and not due to erroneous rain measurement. To overcome the effect of natural rainfall variability, stringent criteria for seedability and suitableness of a day for experimentation need to be defined. Till recently, seeding was done on all days, randomly allotted to seeding, without proven physical model or well tested predictors as guides to objectively screen out days not helpful to effective cloud seeding. This resulted in reduction of the power of the statistical tests employed and made longer experimentation necessary, to acquire bigger sample size required, to resolve the seeding effect at an acceptable level of significance.

The other factor which affects the size of the sample required and thus the statistical design of the experiment is the magnitude of the seeding effect. The main difficulty in increasing the magnitude of the seeding effect is the lack of technology to precisely target the seeding reagent at opportune moments, at the proper place and in just the required size and concentration. Although tremendous advances have taken place in the direction by the use of aircraft, better pyrotechnics, encapsulated seeding mixtures, precise cloud parameter measurements and doppler radars, etc., the seeding technology has not come up to the optimum requirements. Concerted efforts are required to understand the clouds and cloud system in their entirety, so that it may be possible to comprehensively describe them. This would enable the experimenter to indicate the direction as well as the magnitude of seeding effects expected under specific conditions of climate, local weather, topography and cloud physical features, etc[61–63].

It was observed during cloud seeding experiments conducted in India that individual convective clouds during the monsoon season have a short life span and low precipitation efficiency. One of the factors that may be responsible for this is the lack of giant condensation nuclei at cloud base level, which is also corroborated by measurements[64]. Under warm seeding hypothesis, this deficiency can possibly be overcome by introducing artificially requisite number of giant condensation nuclei to accelerate condensation-coalescence process in them, and thus leading to enhancement of rain. This was done by dispensing in developing cumulus clouds as well as in their surroundings, a micropulverized mixture of common salt and soapstone, in the proportion 10 : 1, with a modal particle diameter of 10 microns. Suitability of the day for conducting the experiment was determined on the basis of amount of convective cloud cover, base and heights of likely clouds and winds up to 3 km height. Such experiments are known as static seeding experiments and rain enhancement expected from them is about 20%.

However, for obtaining significant increase in rainfall the real hope lies in successfully conducting dynamic cloud modification experiments, wherever feasible. To reduce meteorological uncertainties a very valuable concept of seedability and seeding effect has been incorporated in the design of these experiments[65]. Seedability is the difference in numerical model predicted cloud top height if seeded and the predicted top height of the same cloud when not seeded. Seeding effect is the difference between measured cloud top height and the predicted unseeded cloud top height.

Every morning, during experimental period, cloud model is run on computer in real time with the morning radio sonde ascent and a calibrated radar, to monitor the area for echo development. Radiowind sondes are used to get the winds at different heights. A monitoring aircraft is used to measure cloud physical parameters and for photogrammetry. Observed environmental data and estimated radius of cloud turrets are fed into the model. Further decisions regarding seeding operations are taken if the simulation results indicate suitability of the day. A very high correlation between seedability and seeding effect for the seeded clouds and no correlation with control clouds was obtained, which indirectly confirmed soundness of the dynamic seeding hypothesis, for the Florida Area Cumulus Experiment.

7. Experimental design—statistical considerations

Logical requirement of a seeding experiment is the comparison of rainfall in a target area when clouds are seeded with an estimate of the rain which would have fallen in the area naturally. In most cloud seeding experiments, rainfall over a control area is used as a predictor variable or covariate for target area rainfall. Other suitable covariates, which would give a measure of those aspects of spatial variability of rainfall which are not adequately covered by the control area arrangements are also being employed to reduce the experiment duration, needed to detect the seeding effect. Such predictors are cloud base height, vertical growth, cloud top temperature, radar echo motion and coverage, wind direction and synoptic conditions, etc[66–69]. Great effort is therefore required to be made in accurate observation, measurement and documentation of several cloud physical and dynamical parameters during actual cloud seeding experiment[70]. Experiments are suitably randomized to avoid chances of bias on the part of experimenters and to improve statistical significance.

Various designs commonly used for cloud seeding experiments along with their merits and shortcomings are briefly described below :

7.1. *Random experimental (Single area randomization)*

The design consists of only one experimental area. The area is seeded or left unseeded as dictated by the randomization procedure. Non-seeded area rainfall data act as control. Only experimental data are used in analysis. Method requires long periods of experimentation for detecting small increases in rainfall due to inherent noise of large natural rainfall variability. In the statistical sense, perhaps, it is the most valid design, since no historical data are used and no dubious assumptions are made. Design is, however, prone to the adverse effect of persistence if it exists. In spite of its poor efficiency, this design was employed in the Florida Area Cumulus Experiment (FACE) in preference to the most efficient cross-over design to avoid possible dynamic contamination of the control area due to seeding in the target area[71].

7.2. *Random historical*

The design involves not only a random choice of days or events to be seeded over a single target area, but also includes the historical data as part of the control data for evaluation of seeding effects. Though there is considerable improvement in efficiency, the design suffers from the inherent defect that the historical data may not be representative of the experimental periods. All designs involving historical data have the drawback that the location and density of raingauge network, vegetation growth and urban and industrial development in the experimental period will be different from the one in the historical period. The design is thus beset with inherent uncertainties in the extrapolation of data to the present or future.

7.3. *Target-control*

Single target area (T) is seeded on a randomized basis and a nearby control area (C) is left unseeded. Control area is chosen such that it replicates the target area as far as possible. Also orientation of the area with respect to the prevailing winds should be such that the control area does not get contaminated when the target area is seeded. Evaluation of seeding effects is based on inter area comparisons of rainfall by T–C differences or T/C ratios. Random variability is to some extent reduced with this design, since most day-to-day variation affects T and C similarly[72]. This design, though requires smaller time, needs high correlation between target and control area rainfalls. The efficiency of the design considerably improves when more than one control area is used[73].

7.4. *Crossover or dual target-control*

In this design paired target areas are set up and either area is seeded at random 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. Thus, data accumulate twice as fast as in a simple target-control design, because an effect of seeding appears in every period. The significance level is usually obtained with the test statistic root double ratio (RDR) defined as,

$$RDR = \sqrt{\frac{T_s}{C_{ns}} \cdot \frac{C_s}{T_{ns}}},$$

which is a geometric mean of the two areas' S/NS ratios, when T_s and C_s refer to area average rainfall over target and control areas on respective seeded days and C_{ns} and T_{ns} to rainfall on the corresponding non-seeded days. RDR has the advantage that it depends directly on the amounts of seeded *versus* non-seeded rainfall as can be seen by rewriting it as

$$\sqrt{\frac{T_s}{T_{ns}} \cdot \frac{C_s}{C_{ns}}}.$$

This design minimizes the noise of natural rainfall variability, because fluctuations of rainfall in the seeded area to some extent get neutralized by the parallel fluctuations in the highly correlated control areas. Pairwise randomization scheme is employed with this design, for preventing possible chain of seeding events over the same area, to mitigate the persistence effect and thus improve its sensitivity and efficiency[74]. But this is liable to a serious objection that, for the second unit the course of action is known in advance to the experimenters who may subconsciously take a biased decision in choosing proper seedable units[75]. This design is considered to be the most efficient one though possibility of dynamic contamination of the neighbouring control area somewhat vitiates the results. Dynamic contamination is serious particularly when the effect in the control area is opposite to that in the target area.

The crossover design requires a high correlation between 'Target' and 'Control' daily rainfalls. This assumes a close proximity of the two areas without causing contamination. As the distance between the areas is increased to avoid contamination, the correlation decreases and sampling period to achieve significance would correspondingly increase. The above conditions are normally quite difficult to fulfil without compromising with the design efficiency.

Further, it appears that the characteristic phenomena of persistence in the natural rainfall or drought, whether a short term day-to-day persistence or a long term version operating on a time scale of weeks or months, have considerable negative effects on the efficiency of seeding experiments[76] particularly those with crossover design[77, 78]. Precautions are thus necessary to avoid the effects of persistence because it is not possible from the rainfall measurements alone to isolate these effects.

7.5. *Floating target*

A floating target means all clouds that are seeded and also includes all those merging with them, so long as they remain in the target area. The analysis area floats or moves with the clouds within the fixed target area. This design was first utilized in the 'Whitetop' cloud seeding experiment[79]. Here the floating target was called the 'plume'. It incorporated the area where the winds carried the seeding reagent. Remaining experimental area, called 'non-plume', formed the control area. This concept has been developed further with the availability of modern radars for accurate quantitative rainfall measurements. During the period of experiment, radars are calibrated with dense raingauge clusters in the experimental area. Randomization is by days. Rainy and disturbed days are screened out. Floating target forms a part of the total target. If the uncontrolled background noise due to large unseeded clouds floating into the target is not serious, floating target rainfall is large and approaches total target rainfall for successful experiments. Floating target rainfall analysis on seeded and non-seeded days provides a more sensitive test of the effects of dynamic seeding. This experimental design has been effectively utilized in multiple cloud seeding experiments[80].

8. Statistical evaluation techniques

8.1. *Unconventional nature of the rainfall distribution*

The problem of statistical evaluation of cloud modification experiments for rain enhancement is complicated by the high natural variability of convective rainfall in space and time. Distributions of rainfall particularly for short periods such as 24 hours are usually discontinuous at zero and are long-tailed due to occasional very heavy rainfall. This unconventional nature of the rainfall data has posed tough questions regarding the choice and validity of standard statistical methods, which are based on the conditions of normality and homoscedasticity of the variates. Seeded and control area rainfall distributions are skew and also do not quite satisfy the condition of homoscedasticity because the conditional variance of the seeded area rain for different values of control area rain is not constant but is found to be very much dependent on the values of the latter. So, optimal tests of normal theory cannot be properly applied to the evaluation of cloud seeding experiments.

Attempts have been made to overcome this difficulty by suitably transforming the rainfall data so that its distribution approaches normal and then to apply the tests of normal theory on the transformed data. But this raises another problem, because now it is the increase in the mean value of the transformed variate that can be estimated and a direct estimate of the increase in the mean value of the untransformed variate may be difficult. In fact, it can happen that the mean of the raw data is decreased while that of the transformed data is increased. This introduces a bias and some correction procedure is necessary[81]. With reference to cloud seeding experiments, it was estimated that the normalising transformation introduced a bias of about 7% in magnitude of the average non-seeded rainfall in the target. Since expected increases due to cloud seeding are of the order of 10 to 15%, this would mean that nearly half the increase is generated by the bias of the statistical anlaysis[82].

8.2. *Variability of the size and nature of seeding effect*

Another crucial problem that needs to be solved before standard statistical methods could be properly applied here is the hypothesis or specification regarding the nature and extent of the effect of seeding. So far, almost everywhere, the results of rain-making experiments have been uncertain, producing increases as well as decreases of different magnitude in the seeded area rainfalls[72, 83–85]. This large and irregular unknown variability in the outcomes of these experiments points glaringly that, the seeding effect is really not known yet. This made Gabriel and Feder[86] to aptly summarize the position thus, "Since so little is known about the alternative one shoud be testing against, it is not only doubtful whether standard techniques are valid but it is difficult to decide what a good technique is."

Thus, on the evaluation of rainmaking experiments we are confronted with two types of abnormal situations :

(i) The test variate, *viz.*, the observed rainfall follows distributions that have not been examined, so that no known most powerful tests are available.

(ii) Even though the distributions are well known, the alternative hypothesis regarding the expected effect of seeding may not be the one for which a standard most powerful test has been devised.

These points are discussed further to clarify the position. Let T and C denote correlated seeded and control area observed rainfalls. We assume that, somehow the problem of normalizing transformation is faultlessly solved. X, Y are the corresponding transformed variables, say, *e.g.*, after a square root transformation.

$$\sqrt{T} = X \text{ or } T = X^2 \tag{1}$$

where X is now normally distributed with probability density function

$$\begin{aligned} f(x) &= \frac{1}{\sigma\sqrt{2\pi}} \cdot \exp \frac{-(x-\bar{x})^2}{2\sigma^2} \\ &= \frac{1}{\sigma\sqrt{2\pi}} \cdot \exp\{-(x - a_0 - a_1\bar{y})^2/2\sigma^2\}, \end{aligned} \tag{2}$$

when for a given vaue of Y, the conditional distribution of X is normal with constant variance σ^2 and coefficients a_0, a_1 are unknown constants. We are here working under the assumption that seeding does not change the variance and the regression coefficient a_1 but it may affect a_0. In other words, seeding is considered to have an additive effect. This is a classical case in which t-test based on normal theory is the optimal test.

But, it is the widely held opinion amongst the meteorologists engaged in cloud seeding experiments that a multiplicative effect of seeding is the approximation nearest to the true effect. Working in terms of transformed rainfall X on the area designated as target (T) and assuming that seeding effect is multiplicative in such a way that, when the non-seeded or control area rainfall is y, the expected rainfall in the target area is

$$E(x \mid y, \xi = 0)$$

and the expected seeded rainfall is

$$E(x \mid y, \xi) = e^{2\xi} \cdot [E(x \mid y, \xi = 0)]. \tag{3}$$

where ξ is the effect of seeding. The factor $e^{2\xi}$ arises due to squaring of the seeding factor e^{ξ} as the seeding effect is on the observed or non-transformed data [T; C]. Since X has a linear regression on Y and it is conditionally normal

$$E(x \mid y, \xi = 0) = a_0 + a_1 y;\ \text{variance } (x \mid y, \xi = 0) = \sigma^2, \tag{4}$$

for the nonseeded case and

$$E(x \mid y, \xi) = a_0(\xi) + a_1(\xi)\, y;\ \text{variance } (x \mid y, \xi) = \sigma^2(\xi), \tag{5}$$

for the seeded case.

Under the assumption that seeding has a multiplicative effect on rainfall, we get from eqns. (3), (4) and (5) the following identities for the seeded rainfall in terms of the observed or non-transformed variable T

$$\begin{aligned} E(T \mid y, \xi) &= [a_0(\xi) + a_1(\xi)\, y]^2 + \sigma^2(\xi) \\ &\equiv [(a_0 + a_1 y)^2 + \sigma^2] \cdot e^{2\xi} \end{aligned}$$

or

$$E(T \mid y, \xi) = E(T \mid y, \xi = 0)\, e^{2\xi} \text{ for all } y, \tag{6}$$

both sides of the identity are polynomials of the second order in y. Therefore equating coefficients of the like powers

$$\sigma(\xi) = \sigma e^{\xi}$$

and

$$\alpha_1(\xi) = \alpha_1 e^{\xi}. \tag{7}$$

The optimality of the test for no seeding effect $\xi = 0$ is now required with respect to the nonstandard alternatives given by (7). And no such tests based on normal theory for fixed sample sizes are known, which have optimal properties to test the hypothesis against these alternatives. We thus find that even under the assumption of normalised distribution no optimal test of normal theory is available for the nonstandard (multiplicative) hypothesis. In such situations we have no alternative except to resort to asymptotically optimal tests[87,88] which are described in the following paragraphs.

It is of prime importance that before a field experiment is undertaken, an estimate of its efficiency and likely power of the proposed statistical tests against various alternative hypotheses available is calculated by using observations akin to those to be obtained with the contemplated design of the experiment. This would greatly help in fixing optimum length of the experimental unit, size of the experimental area and in estimating the period required to achieve significant results. A number of experiments which proved unproductive and caused a lot of confusion and controversies in the field could have been stopped in the earlier stages if the researchers had a real understanding of the nature of seeding effect; further not it is possible to calculate the power of a test unless the alternative hypotheses, to be tested, are also specified. Various possibilities regarding the treatment effect including the design for a variable effect model have been discussed by Neyman[89], Kulkarni[90] and Moran[91]. In fact, it has been found by Kulkarni[90] from analysis of the Canadian cloud seeding experiment data[92] that the results of the experiment are non-significant when tested for fixed seeding effects but are significant when tested for variable effects.

8·3. *Optimal $C(\alpha)$ and generalized likelihood ratio tests*

With a view to remove the difficulty due to large natural variability in rainfall, Neyman and Scott[93] developed optimal $C(\alpha)$ tests for evaluation of cloud seeding experiments These tests are especially suitable when the anticipated treatment effect is not additive and the rainfall distribution is skew. Optimal $C(\alpha)$ test is asymptotically locally most powerful under the circumstances, when the rainfall fits a gamma distribution and the expected seeding effect is either a multiplicative increase or decrease in rainfall. Moreover, the test is insensitive to mild departures of rainfall from gamma distribution. This distribution is observed with experimental areas of medium size and units of the order of a day. In such cases the rainfall probability density function is given by

$$p(y \mid \gamma, \delta) = \frac{\delta^{\gamma}\, y^{\gamma-1} \cdot e^{-\delta y}}{\Gamma(\gamma)}, \quad \gamma > 0, \delta > 0, y > 0.$$

The 'asymptotic test' reckons here the limiting probability as the sample size is increased. The asymptotic power $\beta(\xi, \alpha)$ can be calculated easily for the optimal $C(\alpha)$ tests, at the specified level of significance α and a fixed multiplicative seeding effect ξ from the two equations

$$1 - \alpha = \frac{1}{\sqrt{2\pi}} \int_{-v(\alpha)}^{v(\alpha)} e^{-y^2/2}\, dy,$$

$$1 - \beta = \frac{1}{\sqrt{2\pi}} \int_{T-v}^{T+v} e^{-y^2/2}\, dy$$

where v is the value of normal deviate at α and y is the control area rainfall, τ is known as a non-centrality parameter. It gives the shift in the distribution curve, produced as a result of seeding. The power β therefore depends on the preassigned value of α through $v(\alpha)$ and on the noncentrality parameter τ. Larger the value of τ the higher will be the value of β, which provides a high capability of separating the real effects from those produced merely by chance. Relation between power of the test, level of significance for various values of τ is computed and depicted in a graphical form by Neyman and Scott[94]. It is shown there that a reasonable precision of the experiment is attained when $\tau \sim 2{\cdot}5$ or higher.

The non-centrality parameter is given by the equation

$$\tau = \Delta \{Np(1 - p)\}^{1/2} \log \xi$$

N = number of experimental units;

p (probability of seeding) = 1/2 in a randomized seed/no-seed experiment.

The equation clearly points out that τ is strongly dependent on the experimental conditions, the anticipated magnitude of the seeding effect to be detected and the variability of the atmospheric conditions.

The factor Δ represents all the important design parameters of the experiment such as the local conditions and variability of rainfall, length of the experimental unit, size of the area and the statistical test employed. Therefore, while designing a cloud seeding experiment attempt has to be made to estimate Δ and to obtain larger values for it by suitably selecting the design parameters that are under experimenters' control. It has been shown[94] that when no predictor variables are utilised and the rainfall has a gamma distribution with shape parameter γ, $\Delta = \gamma^{1/2}$.

This gives a very useful formula for computing the size of a proposed experiment or the number of units N required to detect the seeding effect to a specified statistical significance level,

$$N = \frac{4\tau^2}{\Delta^2 (\log_e \xi)^2}.$$

If some predictor variables are utilized and the target rainfall X has a linear regression on the predictors with constant conditional variance, then

$$\Delta^2 = E\left[a_0 + \sum_{i=1}^{n} a_i y_i\right]^2 \Big/ \sigma^2$$

gives the required value of Δ. It has been further shown by Neyman and Scott[94] that by including simultaneous observations of properly selected physical covariates in the design of an experiment, the period of experimentation required to achieve significant results is dramatically reduced. It is shown, for example, that the use of three properly chosen physical covariates as predictors reduced the experimental units by nearly a factor of four.

An efficient likelihood ratio test has been developed by Schickedanz and Krause[95] for testing the significance when the rainfall data fits a gamma distribution. This test is based on the variation in the scale parameter between seeded and control rainfall distributions having same shape parameter. This test is equivalent to testing if the multiplicative effect ξ is equal to 1, *i.e.*, no effect and is based on asymptotic theory, thereby implying large sample sizes. The condition of same shape parameter for both the seeded and control rainfall restricts the wider applicability of this test. In non-standard situations, moreover, maximum likelihood estimates are found difficult to calculate.

Optimal $C(\alpha)$ test is asymptotically most powerful for the hypotheses of additive or multiplicative effects of cloud seeding on rainfall, provided the alternative to be tested is correctly known. But it is found that if the true nature of the effect of seeding is misjudged, by assuming an additive effect when in reality it is multiplicative or *vice versa*, the efficiency of the test is considerably reduced. In fact, in some of the cases use of wrong criterion may tantamount to reduction in number of observations[93] by a factor of nearly 5. Kulkarni[90] has developed the test further to derive the optimality criteria for testing the variable effects of a treatment for general experimental design, of which fixed target-control or crossover designs are special cases.

8.4. *Bayesian statistical analysis applied to cloud modification*

Because of the time and cost factor involved in conducting cloud modification experiments, it is very important to utilize all the information that one can have. The main weakness of most of the existing statistical approaches is that they do not permit us to use all that we really know. The available methods are not at all wrong but they are inadequate[96]. The Bayesian approach is a part of the development towards more effective utilization of all relevant data in statistical analysis. It gives weightage to the existing data and enables to determine not only the direction of the seeding effect but also its magnitude. Simpson[97] and her group were the first to adapt the technique of Bayesian analysis to weather modification experiments, A simplified exposition of the analysis as applied to cloud seeding experiments is given by Sharma and Kapoor[98] and is briefly presented here.

The basic idea underlying the Bayesian technique is the assignment of prior probability to one or more test variables. It is quite appropriate and logical to assign a prior probability to the variable of maximum interest and about which there is some physical knowledge. 'Prior' assignment of probability to the truth of hypothesis about the variable, corresponds to an 'encoding' of the knowledge before performing an experiment and collecting data.

Prior opinion expressed in the form of a probability distribution can usually be closely approximated by one of just a few common distributions that are easy to use in Bayes' theorem. The aproximation may be a member of a natural conjugate family or a vague prior. A gamma distribution is perhaps the most suitable, because of its great mathematical tractability and its ability to incorporate a wide range of prior information. Moreover, daily rainfall data over medium sized experimental areas are often found to closely fit a gamma distribution. An approximate prior distribution can be used if the posterior distribution that results looks virtually identical to the posterior that would have been obtained had the actual prior distribution been used[99].

Prior probability distributions are changed by the data to yield posterior probabilities through the application of Bayes' theorem. The theorem automatically weighs the relative contributions of prior and sample data to the posterior probability distribution. By employing numerous classes and distributions of priors to the seeding factors, with data fitting a gamma distribution, Simpson[97] concluded that arbitrary assignment of prior probability does not seriously affect the results. However, since the choice of a prior affects the sensitivity of the analysis and is considered to incorporate available information and physical knowledge about the variable, full justification must be given for adopting a particular prior distribution.

Bayesian analysis

Rainfall (x) can quite often be fitted into gamma distribution whose probability density function is given by

$$p(x) = \frac{\delta^{\gamma} x^{\gamma-1} \cdot e^{-\delta x}}{\Gamma(\gamma)}, \quad \gamma > 0,\ \delta > 0,\ x > 0 \tag{i}$$

where γ and δ are the shape and scale parameters respectively. Γ is the gamma function[100, 101].

Its mean (μ) and variance (σ^2) are,

$$\mu = \langle x \rangle = \gamma/\delta;\ \sigma^2 = \gamma/\delta^2. \tag{ii}$$

Suppose that seeded and non-seeded data can be separately fitted into gamma distributions with nearly the same shape parameters, and scale parameters, δ_s and δ_c respectively. Also, let $\langle x \rangle_s$ and $\langle x \rangle_c$ be the expected values of rainfall for seeded and non-seeded distributions. Let the seeding factor F be defined by,

$$F = \frac{\langle x \rangle_s}{\langle x \rangle_c} = \frac{\delta_c}{\delta_s}, \tag{iii}$$

where the last ratio is obtained by virtue of first of relations (ii). A smaller value of δ_s, therefore, implies more rainfall in seeded cases compared to non-seeded ones. Also let the effect of seeding be multiplicative.

By virtue of relation (iii), we can make use of Bayes' equation for the scale parameter δ to determine the actual seeding factors. Bayes' equation for δ is,

$$p(\delta \mid S) = p(\delta) \frac{p(S \mid \delta)}{p(S)} \tag{iv}$$

where

$p(\delta \mid S)$ = Posterior probability density distribution of the scale parameter δ in reference to the seeded data, S,

$p(\delta)$ = Prior probability assigned to the scale parameter,

$p(S \mid \delta)$ = Likelihood of the seeded data for the scale parameter,

$p(S)$ = Probability of the seeded data.

Thus, if the prior distribution of δ and the likelihood function are known, posterior distribution of δ can be computed. Considering different discrete values of prior F and the expected value of control rainfall, $\langle x \rangle_C$ (assumed equivalent to non-seeded average rainfall) expected values of prior were computed from the relation,

$$\langle \delta \rangle_s = \frac{\gamma}{\langle x \rangle_s} = \frac{\gamma}{F \langle x \rangle_c}, \tag{v}$$

which is derived from relations (ii) and (iii).

Bayes' equation (iv) can be solved by assuming prior probability distribution of δ either a gamma function or a uniform distribution. In the following analysis a prior gamma distribution has been assumed for δ to simplify the analysis and because of the ability of this distribution to incorporate a wide range of prior information. This does not limit the scope of the analysis though sensitivity is somewhat affected by assuming peaked or flat gamma distributions[102].

In the beginning of the experiment a spread out prior distribution of δ is preferable, though it would be best to assign a uniform prior distribution to δ within a wide range of seeding effects to avoid any bias on the posterior δ

$$p(\delta) = \frac{K_2^{K_1} \delta^{K_1 - 1} \cdot e^{-K_2 \delta}}{\Gamma(K_1)} \tag{vi}$$

where K_1 and K_2 are respectively the shape and the scale parameters.
Prior

$$\langle \delta \rangle_s = K_1 / K_2. \tag{vii}$$

K_2 is calculated from this relation for an assumed value of K_1.

Since the seeding trials are independent, the likelihood function $p\ (S|\delta)$ can be written as,

$$p(S\,|\,\delta) = \prod_{i=1}^{n} \frac{\delta^{\gamma}\, x_i^{\gamma-1}\, .\, e^{-\delta x_i}}{\Gamma(\gamma)} \tag{viii}$$

where n is the number of seeded cases.

Substituting (vi) and (vii) into (iv), the gamma distribution for posterior δ_s is given by

$$p(\delta\,|\,S) = \frac{(\sum_{i=1}^{n} x_i + K_2)^{n\gamma+K_1}}{\Gamma(n\gamma + K_1)}\, .\ \delta^{n\gamma+K_1-1}\, .\, e^{-\delta(\sum_{i=1}^{n} x_i+K_2)} \tag{ix}$$

Its shape parameter is $(n\gamma + K_1)$ and scale parameter is $(\sum_{i=1}^{n} x_i + K_2)$.

The expected value of posterior δ_s is, therefore,

$$\langle\delta\,|\,S\rangle = \frac{n\gamma + K_1}{\sum_{i=1}^{n} x_i + K_2} = \frac{\gamma + K_1/n}{\bar{x}_i + K_2/n}\, . \tag{x}$$

With this posterior $\langle\delta\rangle_s$, the actual seeding factor F can be computed using relation (v). When shape parameter K_1 of prior δ distribution exceeds about ten, the posterior gamma distribution tends to Gaussian. Use of Bayes' equation enables us to obtain a probability distribution for the seeding factor F, from which we can know the expected value of seeding factor and its confidence limits.

The chief merit of the Bayesian technique as seen is that it can be applied sequentially; the posterior probability from the first stage of experimental work serving as the prior probability of next stage. This method is therefore specially useful in the evaluation of cloud seeding experiments, where data are being collected in stages. As evidence is being gathered, one can stop and see if the current posterior opinion determined by applying Bayes' theorem is sufficient to justify terminating the experiment. This is invaluable in the decision analysis, when it is required to know in advance the number of years of experimentation required to establish a postulated range of seeding effects.

An essential requirement for applying Bayesian analysis to cloud seeding experiments, however, is that the distribution of natural rainfall over the area should be known and is assumed to remain stable in time. It is usually unrealistic to assume that the natural rainfall distribution is completely known. A somewhat more realistic situation, *viz.*, that the shape parameter γ of the gamma distribution is known and invariant has been presented. The assumption of γ being known effectively takes the dispersion of the distribution as known. In cloud modification experiments there would appear to be serious doubts about the use of prior information because of likely changes of the relevant distribution with time, due to climatic trends, variation in storm types or man-made changes in the environment. The Bayesian theorem has been applied to the scale parameter δ. A satisfactory or practical Bayesian analysis, however, still remains to be developed when all the three parameters γ, μ_c and ξ are unknown.

Bayes' method appears to be quite rational as well as natural considering its utility. It is presented as an additional powerful technique for evaluation of cloud seeding experiments where basic conditions of the analysis are fulfilled.

8.5. *Non-parametric tests*

There are basically two methodologies of statistical inference, the parametric and non-parametric. In the previous paragraphs an assessment of the presently available parametric tests, for evaluation of cloud seeding experiments, has been made. The parametric tests mainly rely on the following assumptions :

(i) observations are independent;

(ii) the distribution of the population is known (usually normal);

(iii) the variances of populations being compared are equal or of known ratio (homoscedasticity of populations);

(iv) measurements are at least on an interval scale.

Because of these clearly defined assumptions a properly applied parametric test is very powerful. However, some or all of these assumptions may not be valid or verifiable when the sample size is small. In meteorological data where considerable spatial and temporal serial correlation exists, assumption of independence of observations is not always likely to be true. Many clever artifices are employed to force a sample distribution into normality for applying a parametric test, even when there is evidence that the distribution is highly skewed, as in the case of daily rainfall data. Fortunately the parametric tests are usually quite effective for moderately non-normal populations. Homoscedasticity of seeded and control rainfalls is taken for granted while evaluating the data of cloud seeding experiments. Parametric tests become inexact and less powerful when their assumptions are violated.

In the non-parametric method no strong assumptions about the population distribution or of the kind mentioned above are made. Assumptions made, if any, are far weaker, that variate is random or that it is continuous, etc, about which there is complete confidence in a given situation. Non-parametric methods therefore work well for a wide variety of populations and are particularly useful when sampling from populations that are far from normal. Some of the non-parametric tests have been adapted and sharpened up for application to the evaluation of cloud seeding experiments[86, 103–108]. Detailed procedure for applying these tests along with the corresponding probability tables of significance values are published comprehensively in the text book of Siegel[109]. Salient features of some of the most efficient non-parametric tests commonly used in evaluation of cloud modification experiments are discussed here;

8.5.1. *The Wilcoxon matched pairs signed ranks test*

The test takes into account differences between pairs of seeded and non-seeded rainfall values with appropriate signs. These differences are firstly ranked irrespective of their signs and the original sign is later affixed to each of the ranks. The test gives more weight to a pair which shows a large difference in magnitude as well as in the direction of change. The Null-hypothesis adopted is that there is no difference between the seeded and non-seeded populations. Under this hypothesis the value of test statistic Z is approximately normally distributed,

$$Z = \frac{T - \frac{N(N+1)}{4}}{\sqrt{\frac{N(N+1)(2N+1)}{24}}},$$

where

T = smaller sum of like signed ranks,

N = number of matched pairs minus the number of pairs whose difference is zero,

significance is tested by referring Z to normal distribution tables.

The power-efficiency of the Wilcoxon matched pairs signed ranks test compared with the parametric '*t*' test under normality assumptions[110] is about 95%.

8.5.2. *Wilcoxon–Mann–Whitney (WMW) test*

This is the most commonly used non-parametric test for evaluation of cloud seeding experiments. It is applicable when the parent population is not known to be a normal distribution. The test is used to search for central tendency (or location) differences between seeded and control area rainfalls. Seeded and control rainfall samples are pooled together and ranked in their ascending order.

Mann–Whitney[111] U parameter is computed

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - T$$

where

n_1 = number of seeded events;

n_2 = number of control events;

T = sum of ranks for sample 1;

provided that n_1 and $n_2 > 8$, it is found that U is normally distributed with

mean

$$\mu_U = n_1 n_2 / 2$$

and

standard deviation

$$\sigma_U = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}.$$

If U is standardised into a normal variate with zero mean and unit variance by Z, where

$$Z = \frac{U - \mu_U}{\sigma_U} = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}},$$

significance is tested by referring to normal (0, 1) probability distribution tables.

The power efficiency of the Wilcoxon–Mann–Whitney test is about 95% of the most powerful parametric 't' test for normal distribution. It is the most efficient alternative to the 't' test, being without the infirmity of restrictive assumptions and requirements of the 't' test[109, 110].

8.5.3. *The Kolmogorov–Smirnov two-sample test*

The test focuses attention on the largest deviation between cumulative frequency distributions of seeded and control rainfall data. If seeded and control values do not differ significantly, their cumulative distributions will be close to each other. However, if they differ significantly at any point, the two samples can be considered as belonging to different populations. Since the test compares the complete form of two distributions and responds to any difference in their location, skewness, dispersion, it is highly useful where normality of data cannot be established or is known not to apply.

Cumulative frequency distributions for the seeded and non-seeded rainfall samples are produced, using the same class intervals. By inspection, largest difference in frequency for a given class between the two samples is found.

Written formally,

$$D = \text{maximum}\,[(F_s\ (xi) - F_c\ (xi)],$$

F_s and F_c are the frequency distributions of the seeded and control samples respectively and i is the class for which D is maximum.

The sampling distribution of D is known and the associated probability tables for different values of the observed D are available[109, 112, 113].

The power-efficiency of this test is about 96% in comparison with the 't' test for small samples and is somewhat reduced for large samples.

Multivariate statistical analysis

The need to generate, use and interpret physical covariates as predictive devices to significantly enhance the power or sensitivity of the experiment is increasingly being felt.

Therefore, accurate concomitant measurements of several cloud physical and meteorological variables together with the rainfall are becoming available[67-70]. Data of some of these variables could be effectively utilized to perform multivariate statistical analysis to yield truly significant results.

However, the determination of realistic multivariate distributions and development of appropriate test function or critical set to be used for a given test becomes highly difficult because of the involvement of the distributions of all the variables. Attempts have been made[80] to extend the procedures employed in two sample (seed/no-seed) univariate ranking tests described by Chung and Fraser[114], Mantel and Valand[115], and Puri and Sen[116]. Though results are not very satisfactory, further developments in the use of multivariate analysis should take place with the detailed and accurate measurements of cloud microphysical, dynamical and environmental meteorological parameters becoming a routine in cloud modification experiments.

8.6. *Choice between parametric and non-parametric tests*

Applications and comparative merits and demerits of parametric *versus* non-parametric tests have been widely discussed by statisticians[108, 109, 117-119]. A major requirement for weather modification evaluation is the development of statistical techniques which would utilize the precious experimental data in the most efficient manner by incorporating all the information that the observations contain. In many non-parametric tests the observations are used only through their rank order or sign, thus wasting the information. On the other hand, if the resolution of the measurements is less than an interval scale, the use of parametric tests would, so to say, add information and generate bias which is as damaging as throwing away of information while using non-parametric tests. If the experimental data satisfy all the assumptions of the parametric test and if the measurement is of the required strength, then non-parametric tests are much less efficient. Under the conditions existing in cloud modification experiments, the efficiency of the powerful optimal $C(\alpha)$ test is quite low. The power at 40% increase of rainfall is of the order of one-half. With the commonly employed non-parametric tests such as Wilcoxon–Mann–Whitney, Kolmogorov–Smirnov test and Median test, etc, this power is much lower (Fig. 6, Page 320 of Neyman and Scott[94]).

It would be beneficial to use non-parametric tests together with the parametric tests to enhance confidence in the results and to provide a stronger basis for drawing conclusions. The non-parametric methods are better utilized in the exploratory phase or test of concept stage of experiments, when nothing much is known about the sampling distribution and where the assumption of normality is clearly dubious.

8.7. *Use of physical covariates or predictor variables in statistical analysis*

It has been rightly pointed out by Simpson[120] that without early identification of proper predictor variables, weather modification experimentation would most likely fail to yield significant results even after a long period of experimentation. Rosenzweig[121] showed that often the use of a proper covariate may prove to be more effective than doubling the sample size in producing conclusive results. Most of the few successes that could be achieved so far in weather modification have resulted due to early identification of stratifications, physical covariates or predictor variables. Here stratification means *a priori* objective quantitative grouping of experimental units with a view to improve the statistical analysis and to maximize the chances of detecting effects of seeding. Simultaneous measurements of physical covariates or predictor variables are required to forecast the amount of rainfall during a particular experimental unit. These covariates are to be those atmospheric parameters which would to some measure reveal the meteorology of local moisture, stability and dynamic seedability conditions, etc. Moreover, these parameters should be easily measurable and independent of whether clouds are seeded or not seeded.

Important predictors that have been used are, for example, precipitable water, mixing ratio, stability indices, cloudbase and cloudtop temperatures, winds aloft, maximum radar echo volume, maximum reflectivity and maximum echo top, previous rainfall in the experimental area during a specified period, etc. From the candidates list of covariates those parameters that have the greatest potential to reduce the natural rainfall variability are chosen by using stepwise multiple linear regression analysis. It is anticipated that if the incorporation of stratification variables and the measurement of proper physical covariates is set forth as a design requirement in the planning stage, this would not only considerably shorten the experimental duration by providing a high probability of reaching an accurate conclusion earlier, but also reduce any bias in the experiment that might inadvertently come in[122-124].

9. Exploratory-confirmatory experiments

Field experimentations in weather modification and multifaceted data analyses, during the last two decades, have brought the realization of the necessity of basic physical understanding, sequential or phased design, predictors and stratifications, and interdisciplinary approach. The concept of distinctive 'Exploratory' and 'Confirmatory' experiments has evolved in the field of weather modification. The 'Exploratory' experiment incorporates phased preprogrammes and subprogrammes, to test the applicability of the modification hypotheses, testing of the physical numerical models to provide stratifications and predictor variables, efficacy and targeting of the seeding reagents to be employed, and the randomization scheme and experimental unit to be adopted[120,125,126].

The exploratory or discovery stage according to Gabriel[127] consists of all conceivable analyses of the experimental results, classified in any reasonable way, with the aim to verify subjective concepts or intuitions about response of different cloud types (tower height, water content, seeding nuclei prevalence, etc.) at different time and space windows in their evolution and to various types and quantums of seeding reagents. In the exploratory data analysis, techniques do not endlessly proliferate but are evaluated and either evolve or get discarded. Scientists in the field of weather modification, these days, are wary to get involved with the randomized confirmatory experimental phase, till sufficient understanding of the underlying meteorological and statistical structure of the meteorological data are established. Design, experimentation and analysis are sequential and cumulative processes. The feedback of knowledge from successful short duration exploratory experiments is hoped to bring in more precision and exactness in the specification of the hypotheses to be tested and thereby optimize the design of the randomized confirmatory experiment[11,127–129].

10. Multiple analyses with postfactum stratifications

Statisticians have performed multiple analyses of the past cloud seeding experiments by the method of postfactum stratification or partitioning of the data, according to factors or variables which were not reckoned or controlled in the original experiment but later appeared meaningful[79, 130–133]. These analyses revealed the high complexity and heterogeneity of meteorological data. In the case of project Whitetop, it was found that both target and control areas received substantially less rain on seeded days which could be either due to overseeding of clouds, seeding unsuitable clouds, spillover of seeding into the control area or to uncontrolled background effects. However, the most puzzling results came from the analyses of Berkeley group of statisticians[130,133] who found the negative effects of seeding extending up to 180 km not only down wind but also upwind of the target and that, deficiencies on '*E*' days partition were not confined to periods following the start of seeding. Their most 'sweeping' conclusion was that, "the negative differences could hardly have resulted from random selection of days for seeding", and, "any conclusions about the effectiveness of seeding one way or the other, that are based on the Whitetop experiment must be made with extreme caution". But, it is to be noted that this result was obtained by adopting a single area randomized experiment design in the analysis in place of the original Target-Control design. In the case of Florida Area Cumulus Experiment (FACE) 'Echo Motion Category' and Climax Experiment 'Cloud top temperature' were revealed as vital stratification variables on the basis of post-hoc analysis[68, 134].

The multiple exploratory data analyses added a new dimension to the past experiments, by exploring all possible dominant controls and interactions in the rain process, and brought about improvements in the design of experiments. But this multiplicity of analyses also produced many problems and futile controversies, especially when the post-hoc analyses appeared to cast doubts about strict adherence to the adopted randomization schemes and a posteriori manipulation of cut off hour of units by the experimenters[11, 133, 135, 136], or fruitless analysis of rainfall data of Swiss Hail prevention experiment in terms of the personal traits of the weather forecasters on duty.

It should be borne in mind that postfactum analysis is exploration, and not confirmation. When multiple analyses are performed, computations of level of significance or confidence based on standard methods no longer apply. Analyses with some stratifications may show physically interesting patterns, which can come out by chance and not as a result of any plausible physical mechanism. In an exploratory phase all the accumulated knowledge or wisdom must be brought into use, to focus the enquiry on at the most a moderate number of main questions. Though one should keep an open mind to the various questions that appear pertinent, the fundamental question that needs to be answered in the confirmatory phase must receive the utmost attention in the exploratory phase to avoid problems of multiplicity[126, 137, 138].

11. Randomized numerical simulation experiments

The enormous physical complexity and natural variability of the interactions between particles and motions at several sizes and scales in the cloud fields, the errors and inadequacies in the measuring systems and seeding nuclei generating and dispensing technologies coupled with the acute lack of knowledge about the possible range and direction of the effect of seeding, have combined in producing too many imponderables, to know, as to what really happens from the nucleus stage to rain. The judgements, so far, were being based on the end product of the complex system, *i.e.*, rain reaching the ground, and no questions were asked about the intervening processes. It is now realized that unless a systems approach is adopted in the field of cloud modification no significant results will be achieved, even with endless experimentation. The experiments, therefore, should be divided into distinct phases, each phase conducting focussed experiment on one or two crucial questions and as the data come, perhaps, a few subsidiary questions can be raised, but never losing sight of the main question[126].

Extensive physical and meteorological measurements have been made, during the past cloud modification experiments, at great cost and labour. The data must be utilized to the maximum extent, keeping in mind the inaccuracies, calibration errors, and the biases, detected in them. Reanalyses of these data, therefore, need to be performed with the new approach, by numerical simulation of natural and seeded clouds with cloud models and by conducting randomized (Monte Carlo) numerical experiments to determine seedability criteria, and to discover dominant control factors, efficient predictor variables, and stratifications. Some numerical studies combining model simulations and statistical methods have been performed with this objective[41, 70, 106, 108, 129, 140].

Several randomized computer experiments have been performed with the historical rainfall data available in different areas, to assess the possibilities of detecting at a specified statistical significance level, the marginal changes in rainfall produced by cloud seeding experiments of a reasonable duration in these areas. In these studies, sensitivities of the various experimental designs and power efficiencies of different statistical tests have been computed by taking into consideration the important controlling factors such as the following : (*a*) the effect of seeding for different types and amounts of rainfall; (*b*) the natural variability of rainfall in the area; (*c*) the density of raingauge network and the errors in rainfall measurements; (*d*) variability of seeding effects and (*e*) the effect of utilizing different meteorological predictor variables[44, 49, 86, 141–144]. These studies demonstrated that natural rainfall variability is the major obstacle to resolution of the seeding effect irrespective of the size of the experimental area. As discussed earlier, an optimum system of rainfall measurement has to be established keeping in mind the requirements of accuracy, cost, manpower and topography of the experimental area to partly overcome the hurdle. The high variability can further be mitigated by adopting stringent seedability criteria to screen out days unsuitable for seeding, developing realistic physical models or predictor variables, utilizing the most efficient tests available and developing new statistical techniques.

At this point, to close the discussion, perhaps one can do no better than to quote Harlan Cleveland from his Foreword to the Report[128] *The Management of Weather Resources, Vol. II*—" The analysis of physical causes and effects is still the bottleneck in atmospheric science. When rational man sets out to produce effects of his own, he is bound to use statistics—' the science of doing science '—as a primary basis for judgements about what he accomplished, compared with what would have happened if Nature had not been altered with a human purpose in view. In the management of weather resources, therefore, statisticians and atmospheric scientists—and analysts of social and environmental impacts, too—must work closely together to decipher the consequences of human intervention. "

12. Conclusion

It is clearly brought out that statistical methods alone are not sufficient in establishing significantly, without any bias, the results of cloud seeding, by undertaking experiment of a reasonable duration. Most efficient approach is a synthesis of improved physical understanding and accurate numerical simulation of cloud processes, the best available measurement techniques and the powerful classical and Bayesian statistical methods applied along with established stratification of data and measurement of physical covariates as predictor variables. It is shown how different powerful statistical tests such as Optimal $C(\alpha)$, likelihood ratio, and Bayesian analysis can be used together with appropriate non-parametric tests to achieve better confidence in results. Confirmatory proof of concept randomized cloud modification field experiments should be undertaken in an area, only after successful completion of ' Exploratory ' experiments in the area. Stratifications must be based on physical principles, and should be *a priori* incorporated into the experimental design, to avoid subsequent problems due to multiplicity of analysis.

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