A REVIEW OF RAINFALL STIMULATION BY MEANS OF CLOUD SEEDING AND ITS POSSIBLE APPLICATION IN THE NATAL CANE BELT

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Introduction

The modern history of rainfall stimulation by means of cloud seeding began in 1945 with the discovery that various substances, notably dry ice, could cause super-cooled vapour clouds to condense into large droplets. In the following year it was found that silver iodide crystals had the same effect on super-cooled clouds, causing them to precipitate ([13]). Super-cooled clouds are those which contain water vapour and liquid water at temperatures below 0°C, and these occur in all parts of the world. Great enthusiasm greeted these discoveries and wild claims were made regarding man's ability to control the weather and to end droughts. However, several large scale projects yielded conflicting results with apparently large increases in precipitation in some cases and decreases in others ([11],[13]).

In particular, Project Whitetop, conducted by Roscoe Braham (1966), and a 5 year Arizona experiment, conducted by Louis Batten (1966), yielded inconclusive results. In the case of Project Whitetop, a 20% reduction in precipitation over an area of 100,000 square miles was recorded ([13]).

Public and scientific interest in weather modification waned throughout the world, partly as a result of the above experiments and also due to the failures of "get-rich-quick" operators, and the whole subject fell into disrepute.

Interest was revived largely by the successes of commercial operators who had persisted in the field in the U.S.A. and who were supplying extra water to large hydro-electric and irrigation dams. Their well-documented operations prompted the authorities to press for further research into the matter. In 1961-62, the American Congress voted $100,000 for research into "increasing rainfall by cloud seeding" and this research is now largely co-ordinated by the U.S. Bureau of Reclamation, as Project Skywater([1]), which is only one of several weather modification projects with vast financial backing. This effort has led to a rapid increase in knowledge in many fields of weather modification and the confusion and apparent contradictions of previous experiments have now to a large extent been elucidated ([1],[2],[3],).

Some theories of super-cooled cloud seeding

In the original or static theory, it was assumed that cloud microphysics should be altered by the introduction of freezing nuclei into a supercooled cloud. Since an average cumulus cloud might contain about 10^{13} litres of supercooled cloudy air, and silver iodide generators provide about 10^{13} nulcei per gram of smoke at -10°C, only a few grams of silver iodide would be required per cloud to provide one ice particle per litre. One litre of cloudy air was assumed to have about one million cloud droplets (10 - 20u diameter) and these should condense to form one rain drop about 1mm in diameter. It was assumed that this would upset the colloidal stability of the cloud. The growth of cloud droplets to precipitation size is explained by reference to the Bergeron Findeison process where the ice particles will grow at the expense of water droplets due to the lower vapour pressure over ice([9],[13]). No consideration was given to the concurrent dynamic effects due to the release of latent heat of fusion or condensation, nor to the effects upon the field of motion of the cloud.

The results from operations based upon the static theory were often disappointing regarding cloud growth and the yield of water ([13]). The dynamic theory involves the releasing of the maximum amount of latent heat of fusion and condensation as rapidly as possible, thereby materially increasing in succession the temperature of the cloud (by 0,5 to 1°C), the buoyancy of the cloud and finally the vertical and horizontal dimensions of the cloud. This increases the lifetime of the cloud and the precipitation from it. More moist air is drawn up into the cloud and this in turn is condensed and eventually precipitated as snow, hail or rain. The technique requires the release of about 20 pyrotechnic flares yielding 50 grams of silver iodide each, for the treatment of one cloud. This dynamic approach, which was largely developed by Prof. Joanne Simpson in Florida, has yielded positive and convincing seeding results ([13],[14],[15],[16]).

The micro-physical : dynamic theory is the most recent and, in terms of extra water produced, is the most successful explantion of the precipitation stimulation mechanism. This theory combines the most recent discoveries in the field of cloud micro-physics with that of cloud dynamics, and this approach appears to hold great promise and may soon lead to an optimising of rainfall stimulation techniques ([4]).

The main results of Simpson's work

Two important results emerge from Simpson's work and her early use of numerical models.

(a) Seedability vs seeding effect

Seedability is defined as "the predicted seeded maximum cloud top height minus the predicted unseeded maximum cloud top height in kilometers".

Seeding effect is defined as "the observed (by aircraft, airborne camera, radar etc.) maximum cloud top height minus the predicted unseeded maximum cloud top height in kilometers". Results obtained in 1965 are shown in Figure 1. If the model and data were perfect, all seeded clouds (circles) would lie along the straight line with slope one, since seedability and seeding effect should be equal for seeded clouds. The unseeded clouds (squares) should lie along the straight line with slope zero, since no matter how high their seedability the control clouds should not grow above their predicted unseeded tops. In Fig. 1, both the means and regressions of the seeded and unseeded populations separate significantly into two distinct populations. Seeding effect vs seedability correlated ot 0,973 (p-0,01) for seeded clouds and was about zero for unseeded clouds. This demonstrates the precision of the model in predicting seeded and unseeded cloud top heights [13].

(b) The second important result to emerge from this work has been the recognition of four basic regimes which will lead to different behaviour in seeded clouds. These regimes are:

(i) *Explosive growth mode:* Seeding will lead to considerable cloud growth and increased precipitation.

(ii) *Cut - off tower mode:* Seeding will lead to decreased precipitation.

(iii) *No growth mode:* Seeding will lead to no increase or a decrease in precipitation.

(iv) *Disturbed. mode:* Seeding will probably lead to no increase or a decrease in precipitation on a naturally rainy day.

The classification of the day on the above basis is made on the results of the 0800 hrs. radiosonde observation and a further observation at 1200 hrs. Should a day be a seed day (mode i) then a computation of the increased precipitation is made after measurement of cloud base, height and diameter ([13,14]).

This work forms the basis for a sophisticated climatological survey method which has been developed by Profs. Simpson and Garstang which, on the basis of analysis of meteorological records and some field study, gives a reasonably accurate picture of the weather modification potential for an area. This is a considerable advance and saving in cost, showing the probable amount of water to be produced by seeding, the unit cost of the water and the changes in streamflow due to the extra water produced ([7]).

A stratification of previous experiments (such as Project Whitetop) has usually shown that the decreases which were so baffling were due to unfavourable synoptic conditions. In general, the greatest response to seeding is on "fair" days with isolated showers ([11,14]).

Prof. Simpson's work has been done mostly with supercooled cumulus clouds in a maritime climate, but most impressive work has also been done by Robert Elliott of North American Weather Consultants, California, U.S.A. on orographic clouds. The records compiled by his company over 20 years of supplying large amounts of water to hydro-electric and irrigation dams in the Sierras have proved invaluable in documenting the reawakened interest in weather modification in the early 1960's ([11,12]).

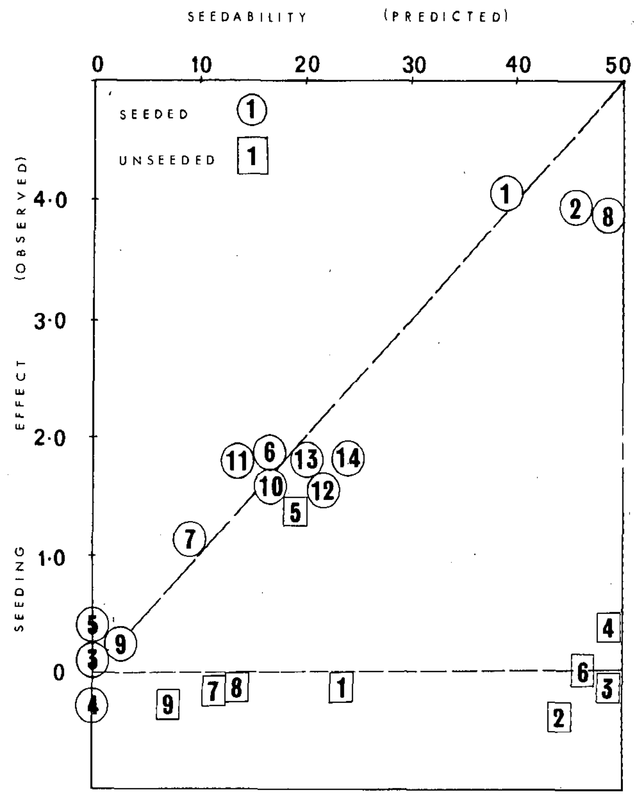

Fig 1 Seedability versus seeding effect for 1965 Caribbean cumulus seeding experiment (See text for explanation

Some theories on warm cloud seeding

Work on warm clouds, i.e. clouds warmer than 0°C, has not progressed as rapidly as that on super-cooled clouds. An intensive effort is now being made to understand the processes involved in the modification of these clouds and numerical models are being developed which are already yielding reliable results. The seeding materials used for warm clouds are strongly hygroscopic such as urea or finely ground salt (NaCl). The insertion of the hygroscopic seeding material causes the formation of a heirarchy of droplet sizes and the mechanism of droplet growth is thought to be primarily due to coalescence caused by the different rates of fall of different sized drops.([4,10]).

Some consideration has already been given to a combination of the "warm cloud/cold cloud" techniques where, in certain cases, a warm cloud might be induced to grow into a super-cooled cloud and then be treated accordingly ([9]). When the techniques for treating warm clouds have been developed to the present stage of reliability of those used for treating super-cooled clouds, then a great deal more moisture will be available for precipitation.

The quantity of water produced by cloud seeding and some cost/benefits to be derived from it

The amount of water produced by weather modification will clearly vary from area to area and from year to year. Some typical in-creases quoted are as follows:

(i) 137 million cubic meters of "new" water per annum in the Upper Colorado River Basin at an estimated cost of R1,00 — R1,50 per 1234 m^3, and an estimated benefit of R20 — R25 per 1234 m^3. (1, Vol. 1 p. 47).
(ii) an increase of 171,2 million cubic metres per annum *in the reservoir* to be obtained from a area of 25 888 sq km. (2, p. 316)
(iii) a 15% increase in stream flow "reasonably anticipated" in the Colorado River Basin or 11 000 sq miles at a cost of R2,30 per 1234 m^3. (2, p. 433)
(iv) 407 220 m^3 of extra water could be produced per cloud in Miami during one normal month (May) and this would produce 165 738 540 m^3 over the area, or an increase of 375mm. and a 23% total increase (13).
(v) The anticipated increase for the Colorado River Basin Pilot Project is now estimated at 30%. (3, p. 95).

In general it would appear that at this stage, increases are of the order of 15% - 40% of annual rainfall (4).

Cloud mergers

It may be noted here that most of the experimental work on cumulus clouds has been done on isolated clouds. Simpson, however, has considerable documentation on "cloud mergers", where a seeded cloud has merged with an unseeded one and the result has usually been a spectacular increase in water production. In one case a merger produced 8797,6 acre ft of water, and it would have taken 36 isolated clouds to produce the same amount of water.

Work is proceeding actively along the lines of inducing mergers by seeding numbers of clouds in rapid succession and so attempting to induce the formation of squall lines, tropical storm bands and giant cumulonimbus systems, which are productive of enormous quantities of water. It should be noted, however, that at this date no sure technique has been developed to predict whether a given day is any more favourable for "mergers" than any other seedable day, or the manner in which mergers can be initiated with certainty.

Some comparative costs of water from conventional sources and from weather modification are given in Table 1. The cost/benefits of seeding will vary greatly with the value and end use of the water produced.

TABLE I

Comparative costs of water produced from natural and artificially induced sources

Water Supply	Costs		Source
	Rand per 1234 m^3	Costs per m^3 cents	(5)
Grahamstown Municipality	136.75	11	
Wemmershoek Dam	40.85	3.3	
Voëlvlei Dam	70.70	5.7	
Sewage Purification High Est.	81.70	6.6	
Low Est.	54.45	4.4	
Orange River Development Project	7.075	0.574	
Weather modification Water High Est.	2.15	0.176	
Low Est.	1.075	0.088	(1,2,3)

Some costs and benefits are quoted in Table 2.

TABLE II

Costs and Benefits of water derived from various sources

Location	Cost per cubic metre	Cost benefit ratio
1. Colorado River Basin	2295 million cubic m. R1./1234 m^3	1:10 (9)
2. Australia (Victoria)	25,000 sq.km "treated"	Cost per annum per acre less than 1 penny. (6)
3. South African equivalent of 2 above	25,000 sq.km "treated"	Cost S.A. 1,5c per hectare.
4. The cost/benefit ratio can be as high as 1:50.		(9)

No critical assessment has yet been made of the value of the extra water produced by the "extra-area effect" (discussed in the next section), but it clearly is large and must be considered from the start of operations.

For standing crops and general pastoral farming, the calculation of the value of the water becomes even more complex. A point which has been appreciated by the Australians is that the timing of the rainfall is often of great importance. It has been calculated that in the Malleen Wimmera wheat growing area of Victoria, Australia, an increase of 25 mm from August 1st to October 31st would give a gain of A £1 million at a cost of A £6 000. (6). Also an increase which might be statistically non-significant might yield high financial returns. The rule of thumb calculation for cane growing is that 100 mm of water gives an extra 9 tons of cane per hectare. Consideration of the S-shaped growth curve common to most agricultural crops indicates that relatively small increases in precipitation around about the mid-point, will give large growth increases.

Where hailstorms are frequent and damaging, the prevention of the formation of hail may be economically as important as, or more important than the production of more water. Severe hail forming clouds can now be successfully treated by cloud seeding ([11],[12]).

Some phenomena assosciated with cloud seeding and their effect upon the evaluation of results and experimental work

A number of phenomena are generally associated with cloud seeding attempts and where those have not been fully appreciated, or ignored, they have seriously confused field studies and experimental results. In certain cases the evaluation methods also were faulty or inadequate.

1. Evaluation techniques and methods

The earliest method of evaluating the success or otherwise of seeding operations was by means of a comparison of two supposedly similar climatological areas, the clouds in the one area being seeded and the clouds (and rainfall) in the other area being left as control. This method is obviously fraught with many difficulties and uncertainties and many years of seeding would be required before any clear result emerged. Comparisons of stream flow records were used in the early stages and these are still most valuable in the evaluation of seeding results ([4],[17]).

The modern methods rely heavily on the use of radar, which is calibrated by means of ground observations, to measure rainfall intensity and duration ([1], [2], [3], [4], [15], [16]). The development of numerical computer models and their use for predictions of cloud growth and precipitation, verified by observations on suitably randomised clouds, have yielded a considerable amount of knowledge.

2. Extra-area effect or large scale dynamic effects

A considerable problem for a long time has been the question of whether extra water was in fact being produced by seeding or whether water was merely being re-distributed.

While the difficulties in the analysis of this problem are obviously formidable, it became apparent many years ago that, while large and predictable increases in precipitation were found in the target area, considerable increases in precipitation were usually found up to 100 miles and more downwind of the target area, and that these increases were as much as 10 times the amount that would normally have fallen there ([2], [3], [4], [7],). While the location and magnitude of these increases or "extra area effects" cannot at this stage be predicted with as high a degree of accuracy as the precipitation in the target area, yet it would appear that the quantity of water produced by the extra area effect is considerably greater than that produced for the target area. This offers further support for the correctness of the dynamic theory of cloud invigoration ([4]).

3. Persistence effects

Briefly, the persistence effect is the tendency for "rain to breed rain and drought to breed drought". This seems to apply to large areas for several seasons as well as the tendency for storms to follow the same fairly narrow path during a season, and this phenomenon may be more apparent in dry rather than naturally moist climates. This natural phenomenon was noted in South Africa ([18]) and Australia ([6], [7]) but to an apparently lesser extent in America. The persistence effect could prove very valuable in the field of weather modification, but any experiments which do not take due note of this may well give conflicting results, as happened with early experiments with a randomized cross-over design for an experiment in the Snowy Mountains in Australia ([6]).

Conclusions and recommendations

The benefits of obtaining greater reliability in what has hitherto been the greatest and most important variable in agricultural production, the rainfall, as well as a reasonable increase in precipitation, are so obvious to the agricultural community that they need not be belaboured here. It is clear that cloud seeding can, under certain conditions, and if properly conducted, produce significant amounts of water very economically. In order to take advantage of this new knowledge in the most beneficial manner, the following lines of approach could be the most productive.

A potential user of water (farming community, municipality, etc) could, after a thorough climatological survey of the area had been carried out, consult with weather modification meteorologists and decide upon the optimum managed climate possible in their area. In all probability this would not differ markedly from a "good average year". Having jointly decided upon this optimum climate and having stated any special considerations regarding floods or the timing of rainfall which might apply, then the cost of attaining this optimum for a period of say 5 years could be calculated.

Having reached this point, the whole operation could be put on an "insurance" basis with, in this case, cane growers being compensated should the climate for any one year deviate too markedly from the optimum.

In view of the shortage of water in South Africa, and the greater and greater demands being made on existing supplies, it is clear that many persons and public bodies will have an interest in weather modification and will want their share of the extra water being produced. This makes it imperative that potential water users, and in particular the farming community, should carefully examine this new technology and decide how best to use it, and how best to incorporate it into their farming systems.

REFERENCES

1. **Anon.**, Atmospheric Water Resources Program "Project Skywater". 1968 Annual Report. Vol. I and II. United States Department of the Interior, Bureau of Reclamation, Division of Atmospheric Water Resource Management, Denver, Colorado U.S.A.
2. **Anon.**, Atmospheric Water Resources Program, "Project Skywater' 1969 Annual Report. (address as in 1. above).
3. **Anon.**, Atmospheric Water Resources Program, "Project Skywater" 1970 Annual Report.)address as in 1. above).
4. **Anon.**, Atmospheric Water Resources Program, "Project skywater" 1971 Annual Report. (address as in 1. above).
5. **Anon.**, Construction in Southern Africa. June 1970 Vol. 15. No. 3 p. 79.
6. **Bowen E.G.**, Cloud seeding Australian Science Journal 1967, C.S.I.R.O., Sydney, Australia.
7. **Bowen E.G.**, Review of Current Australian Cloud Seeding Activities C.S.I.R.O. Sydney Australia.
8. **Garstang M.**, Personal Communication Brooks Museum, University of Virginia, Va. U.S.A.
9. **Heimstra L.A.V.**, Kunsmatige neerslagvermeerdering: 'n ½ sent per 4546 liters ekstra water? Die Siviele Igenieur in Suid Afrika, Julie 1970.
10. **Heimstra L.A.V.**, Kunsmatige Vermeerdering van Reenval. Departement van Siviele Ingenieurswese Universiteit van Stellenbosch. Februarie, 1970.
11. Proceedings of the First National Conference of Weather Modification sponsored by: Amer. Met. Soc. Albany, New York, U.S.A. April - May 1968.
12. Proceedings of the Second National Conference on Weather Modification sponsored by: Amer. Met. Soc. Santa Barbara, California, U.S.A. 1970.
13. **Simpson, Joanne.**, Cumulus Cloud Modification Progress and Prospects. Repr. "A Century of Weather Progress. Amer. Met. Soc. U.S.A. 1970.
14. **Simpson, Joanne.**, Seeding Cumulus in Florida: "New 1970 Results" from Science.
15. **Simpson, Joanne.**, On Cumulus Entrainment and One-Dimensional Models. Repr. Journal of Atmospheric Sciences, Vol. 28, No. 3. April 1971. pp 449 - 455.
16. **Simpson, Joanne.**, How to Build Clouds and Bring Rain. Farmers Weekly, Nov. 12 1971.
17. **Sopper, William E., Heimstra, L.A.V.**, Effects of Simulated Cloud Seeding on Streamflow of Selected Watersheds in Pennsylvania. Repr. Water Resources Bull., Journal of the American Water Resources Assn. Urbana, Illinois 61801, U.S.A.
18. **Whitmore, J.S.**, Technical Bulletin Report No. 25, 1962. Dept. of Water Affairs, Patterson Building, Pretoria, Rep. of South Africa.