A PRELIMINARY ASSESSMENT OF THE POTENTIAL OF ARTIFICIAL STIMULATION OF RAINFALL IN THE NATAL CANE BELT

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Abstract

A study of rainfall stimulation was made with the aim of assessing its economic potential for the Natal cane belt.

High variability of precipitation in both space and time makes the determination of requirements and effects of large scale seeding programmes very difficult.

Evaluation of field and laboratory tests have, however, identified two conditions under which seeding could increase precipitation efficiency and these have been used in this study. The theory was used in two numerical models, designed to simulate cloud growth and development, in order to estimate the number of days when hygroscopic seeding or ice-phase seeding would have been successful.

The analysis of Natal's climatic conditions indicates that a more detailed cloud census and a better measurement of their environmental conditions is essential for a realistic appraisal.

Introduction

Four years ago Hughes[1] presented a paper to this congress entitled "A review of rainfall stimulation by means of cloud seeding and its possible application in the Natal cane belt". He explained the work being conducted by Simpson[2] and her results obtained by means of numerical cloud models. Hughes suggested that the results showed great promise for conducting a climatological survey of the seeding potential of an area like the cane belt, using such a model.

The complexity of cumulus processes and interactions is so great that, despite progress made in numerical modelling, it is still in its infancy. All models are, of necessity, so delicately poised upon hierarchies of assumptions and simplifications that, while their use in guiding and evaluating weather modification attempts is of great value, no model can at present be expected to replace actual measurement. The cost of experimentation to determine the seeding potential of an area is high and therefore the relatively inexpensive use of a numerical model in a preliminary assessment of this nature is justified.

This study was undertaken with a view to assessing the seeding potential of the Natal cane belt by carrying out the following:

(1) An evaluation of cloud seeding; the experiments conducted and their results as well as commercial or large scale augmentation programmes.
(2) Determining the conditions required to obtain successful seeding, in order to augment the natural rainfall.
(3) An analysis of the general Natal coastal conditions of cloud types and frequencies.
(4) An assessment of the seeding potential for each day by means of a thermodynamic diagram or numerical cloud model, and the atmospheric profiles of temperature and humidity.

1. *Evaluation of cloud seeding*

Because of the high variability of precipitation in space and time, and because its distribution departs from the normal distribution on which most statistical tests are based, long series of experiments are required and special evaluation techniques must be used to prove the success of seeding. Most attempts to modify the weather have not been designed to meet rigorous statistical standards. A considerable amount of controversy has resulted, with enthusiasts convinced of success by evaluations not always considered to be valid by critics and statisticians. A listing of the experiments that have been or are being conducted in weather modification would be far too large to be included here. However, a review conducted in 1968 by Neyman and Scott[3] showed that 23 experiments had been conducted which met the requirements of statistical design and adequate duration to produce significant results. Of these, six indicated larger amounts of rainfall when seeding took place than would have occurred naturally. Seven of the others were indefinite, showing an increase or decrease, depending on the portion of the target studied or the method of evaluation used. The remaining ten experiments indicated a definite decrease in precipitation with seeding, below that which would have been expected without it. Further investigations have shown that there are physical reasons why one would expect that, under some circumstances, cloud seeding would decrease precipitation rather than increase it. A brief explanation of these physical processes and the reasons why some instances produce increases and other instances decreases is given later.

Many investigators[4] have found that, particularly in ice-phase seeding (see next section), the increase from single clouds may be enormous (>100%). However, after much controversy, most people now accept that large scale effects do not produce an increase of more than 10-20% of the annual precipitation.

2. *Cloud seeding criteria*

Two basic forms of cloud seeding, in order to stimulate rainfall, have evolved with the relatively recent proposals and experimentation based on a scientific knowledge of the physical processes involved in cloud development. The first and most common form, generally referred to as ice-phase seeding, relies on the freezing characteristics of the atmospheric nuclei in certain clouds. The other form, hygroscopic seeding, relies on the rate at which larger than average cloud droplets develop and grow to raindrop sizes.

(1) Ice-phase seeding

It is common knowledge that, in the atmosphere, stable clouds do exist in the liquid state down to temperatures of −20°C and colder. This is due to the relatively few freezing nuclei, at high altitudes, that are activated above −20°C. Since silver iodide (AgI) has a freezing threshold of approximately −8°C it can be dispensed into clouds, the tops of which are at temperatures in the region of −8°C to −10°C (~6 km), to initiate the freezing of the supercooled water. Two important effects are encountered with AgI seeding of these clouds:

(*a*) The rapid transfer of vapour to the ice nuclei (crystals) at the expense of the liquid water drops. As there are far fewer ice-crystals than water drops or droplets this enables larger particles to grow with the distinct possibility that they will have sufficient mass to overcome the updraught and will fall out as precipitation. This form of seeding is generally referred to as "static" ice-phase seeding.

(*b*) The release of latent heat of fusion.

Under certain conditions the release of latent heat of fusion may enable the cloud to penetrate a shallow stable layer in the upper atmosphere and thereby grow to much larger dimensions. Under these conditions "dynamic" ice-phase seeding will invariably lead to significantly more precipitation than for similar unseeded clouds.

For clouds that have reached high altitudes (i.e. temperatures of −20°C or less), where sufficient ice nuclei are available, a distinct possibility exists that the addition of any further nuclei by AgI seeding will lead to a decrease in the resulting precipitation as a result of the smaller average mass of precipitation particles.

(2) Hygroscopic seeding

Initially clouds consist almost entirely of very small droplets which do not possess sufficient mass (i.e. gravitational force) to overcome the updraughts within the clouds. With collision and coalescence, a few larger than average droplets develop, which move relative to the smaller ones. The relative movement of these larger droplets through the smaller ones accelerates the growth of the former. The rate of the collision and coalescence processes is dependent on the initial concentration and size distribution of the cloud droplets. For short duration clouds with high concentrations and narrow dispersion, the rate of drop growth will not allow the precipitation particles sufficient time to reach fallout size and will therefore result in little or no rainfall.

Introduction of giant hygroscopic nuclei or water droplets (approximately 50 μm) into the inefficient, non-precipitating clouds will increase the droplet radius dispersion factor and therefore the rate of collision and coalescence. Since raindrops will eventually reach a certain size (approximately 5 mm) where they become unstable, the break up of drops of this size into a number of smaller drops will allow a rapid increase in the larger droplet concentration.

Hygroscopic seeding of clouds which have a sufficiently broad spectrum of particle sizes will have little effect on the rate of drop growth but may increase the concentration sufficiently to stop the drops reaching fallout masses. However, the concentration of seeding nuclei would probably have to be extremely high for this decrease to occur.

3. *Natal climatic conditions*

Most of the cloud and rainfall along the coast of Natal can be associated with three main features.

(1) Passing, large scale systems

Passing, large scale systems which develop in the southern Atlantic and move round the east coast of southern Africa. These systems often take on the appearance of cold fronts preceded by a shallow coastal low which has been related to a leader front caused by pre-frontal cooling.[5] In advance of these coastal lows moving up the coast, north-easterly winds bring in warm, moist air from over the seas which, in the late afternoon or evening, may cause the formation of low, stratus type clouds and occasional rainfall.[6] With the passage of the coastal low and front, the winds back suddenly to the south-west, bringing in cool maritime air which generally results in heavy low stratiform clouds with rainfall. These depressions may, on occasion, extend to high altitudes and cover large parts of the sub-continent of southern Africa, bringing widespread precipitation. However, they are often shallow, in which case they do not extend more than 40 to 60 kilometres inland from the coast.

The prolonged, steady release of precipitation from the extensive, deep layer clouds associated with the passage of these depressions and following anticyclones, in which there is little or no supercooled water below −5°C, suggests a quasi-steady state dominated by the dynamics. The processes of nucleation and particle growth adjust themselves to match the rates at which moisture is released by the slow steady vertical ascent. It is unlikely that ice-phase seeding or hygroscopic seeding will have a major effect on the intensity or duration of the precipitation, but they may effect some redistribution on the ground.

Radar has revealed[4] that cyclonic cloud systems, even frontal systems well removed from the active centres of depressions and sustained largely by widespread and prolonged ascent, usually contain much small and meso-scale structure in the form of convective elements, precipitation streamers, topographical disturbances, etc., which may contribute significantly to the water balance of the cloud and certainly influence the intensity and local distribution of rainfall. Little is known about the role of these small and meso-scale disturbances and no modification experiments appear to have been conducted on them. If they are similar in structure to the isolated cumulus, as in the case of stratocumulus, and contain updraughts of more than 1 ms^{-1}, then there is a small possibility that they may react favourably to hygroscopic seeding.

(2) Orographic clouds

With a light on-shore breeze, particularly in the late afternoon or evening, the forced ascent of relatively warmer moist air over the coastal escarpments induces low stratiform clouds. These may, on occasion, penetrate into an unstable layer and generate larger cumulus convection.

The slow, prolonged ascent over the surface barrier produces stratus clouds similar in structure to the large-scale frontal systems and these are therefore unlikely to respond favourably to seeding. However, where the ascending air penetrates a warm layer to initiate large convective cells these may well develop into situations described as seedable.

(3) Convective clouds

As already mentioned, both the cyclonic and orographical situations may deepen sufficiently to induce convection cells, but the greater majority of these clouds appear to originate further inland. Such storms are characterised by far smaller dimensions and much larger updraughts than the extensive deep layer type clouds.

The development of large cumulus or cumulonimbus clouds over the Natal interior (Drakensberg escarpment) has been closely associated with the movement of an upper atmospheric trough (cooling) in the general westerly circulation and the occurrence of a coastal low and northeasterly gradient wind at the surface. These storms generally move with the upper westerly winds towards the east and, if sustained long enough, may reach the coast. The actual conditions leading to the generation of these storms over the higher interior is not well known as they develop at a considerable distance (~ 100 km) from and at higher altitudes than Durban, from which upper atmospheric temperature and moisture data are available. It thus appears that, for the areas east of the Drakensberg, having an elevation of less than 1 000 m (coastal belt) convectional processes are inefficient and, on their own, contribute little in the way of rainfall because of the combined effects of the near surface temperature inversions in the divergent north-easterly wind-flow, and the mollifying influence of the sea on land surface maximum temperatures. In effect, apart from the warm rain type showers experienced at the coast when the entire body of the cloud is below the height of the freezing level, towering cumulus resulting from purely convective processes is confined to the region having an elevation greater than 1 000 m. Below this elevation convergence associated with frontal uplift, or the under-cutting of conditionally unstable air, accounts for the development of showers or thunderstorms over the coastal escarpment, but by far the greatest volume of precipitation is derived from combining these processes with the orographic building up against the escarpment with an on-shore coastal wind.

4. *Numerical analysis*

In numerical models of convective cloud growth it is assumed that development is due entirely to localised buoyancy forces which develop on account of the temperature differences between the cloud air parcel and the stratified environment. Since the conditions of temperature, moisture, and pressure (height) at cloud base will define the eventual cloud temperature profile, and hence the resulting dynamics, they are critical in any numerical analyses. In a similar manner the environmental profile of temperature will also define the resulting dynamics. It therefore becomes imperative that accurate measurements of the environmental temperature and moisture in which the clouds are developing, and their conditions at cloud base are obtained for a realistic appraisal of cloud seeding potential.

The atmospheric profiles of temperature and moisture (radiosonde sounding) are obtained twice daily, by the Weather Bureau at Louis Botha airport, as well as observational estimates of cloud type and approximate base height. It should therefore be possible, with a reliable numerical model, to assess the coastal development of clouds. However, the reliability of this sounding further inland is doubtful as we have already noted that the coastal inversion seldom extends far from the coast. It is not possible at this stage, therefore, to assess with any degree of reliability the seeding potential of clouds developing over the midlands and moving towards the coast as there are no other stations in Natal that obtain these measurements.

(1) Skew T-log p analysis for Durban

Both the 02h00 and 14h00 SAST radiosonde soundings from Louis Botha, when available, were analysed by means of a Skew T-log p computer model for the summer months of 1974/1975. The analysis confirmed that, on nearly all occasions, a low level inversion exists at the coast, the height and magnitude of which appear to vary with the passage of a depression along the coast or the changes in wind direction associated with passing depressions. A histogram of the heights of the inversion, given in Figure 1, shows that it seldom extends beyond the freezing layer, thus confirming that the majority of clouds at the coast are confined to the all-water situations.

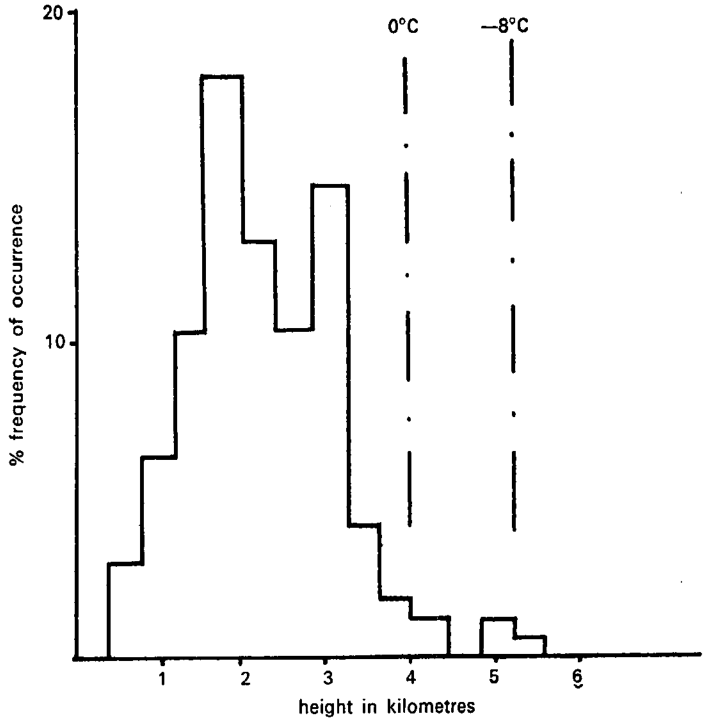

FIGURE 1 Histogram of the height of the inversion during the period October 1974 to May 2, 1975.

Further analysis indicated four days (<3%) during the period October 1, 1974 to May 2, 1975, that had clouds with tops in the region of 0°C to −10°C, the requirements for AgI seeding. Dynamic AgI seeding would probably have enabled clouds on 27/1/75 to penetrate the shallow inversion and develop to far larger dimensions than any corresponding unseeded ones. The other three cases, however, had a stable layer extending well above this level and it is doubtful if dynamic AgI seeding would have induced any large scale development. If, however, they contained few ice-phase nuclei static AgI seeding might well have induced an increase in rainfall. An estimate of the benefits probably derivable from seeding on these four days can be gauged from the rainfall recorded at four stations in the sugar belt and given in Table 1.

None of the stations had excessive rainfall in either the preceding or the following week although rainfall on 13/2/75 was high enough not to warrant further increase by cloud seeding.

(2) Steady-state numerical model[8]

A steady-state, one-dimensional model in current use at Nelspruit for hail prediction was obtained and run on all available 14h00 SAST radiosonde soundings from Louis Botha for the same period (October to May). The model[8] has been found to be fairly reliable for large convective storms in the Transvaal Lowveld. However, for the Natal conditions (maritime), where most clouds are below the freezing level and seldom develop under purely convective conditions, the reliability had to be checked.

TABLE 1

Rainfall (mm) for the four days indicated and totals for the preceding and following weeks

Station	Previous week	27.1.75	Following week	Previous week	12 and 13 February		Following week	Previous week	20.2.75	Following week
Tongaat . . .	74	5	37	13	10	40	34	73	8	52
Experiment Station	43	Nil	29	8	14	50	33	80	3	18
Sezela	44	Nil	17	57	22	36	62	95	2	35
Jaagbaan . . .	48	10	14	8	2	37	52	80	9	10

TABLE 2

Steady-state numerical predictions of natural rainfall (a) in mm and the predicted percentage increase due to hygroscopic seeding (b) for a cloud with an initial updraught radius of 1 km and velocity of 3 ms^{-1}

Day	October		November		December		January		February		March		April	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
1 . . .			3	64	0								2	101
2 . . .	3	62			26	8			2	124				
3 . . .	0				34	11	2	60	0		5	46	9	42
4 . . .			0						0		22	18	10	51
5 . . .			0		1	48			3	?			0	
6 . . .			4	60			0		1	65	0			
7 . . .	6	54	2	67			1	50	1	88	4	39		
8 . . .	0								3	65	10	27		
9 . . .							2	51	3	47	11	15		
10 . . .					0				1	93	4	64		
11 . . .			0		2	71	3	59			3	76	1	128
12 . . .					23	20	2	68	25	11	6	50	6	50
13 . . .					1	59	0		26	9	2	72	16	49
14 . . .	2	75							3	87	14	38	10	32
15 . . .			0		2	105	1	75			9	50		
16 . . .	2	98			2	42					0		20	30
17 . . .	0						6	48	3	52	3	50	14	43
18 . . .	1	100	0		0				3	83	3	43	1	184
19 . . .			5	22	2	44	4	45			15	40		
20 . . .							2	89	0		3	83	1	176
21 . . .	2	101	1	109	2	96							21	31
22 . . .	0		1	137			1	131	4	61				
23 . . .					2	65			9	40				
24 . . .	0				2	86			3	80	35	20	39	12
25 . . .			0		2	106					7	36		
26 . . .			1	114					2	69	1	158		
27 . . .	8	50	7	43					1	88	8	55	0	
28 . . .									2	60			0	
29 . . .	0		4	74	1	121							4	74
30 . . .							4	53					5	54
31 . . .	0				0		1	130			0			

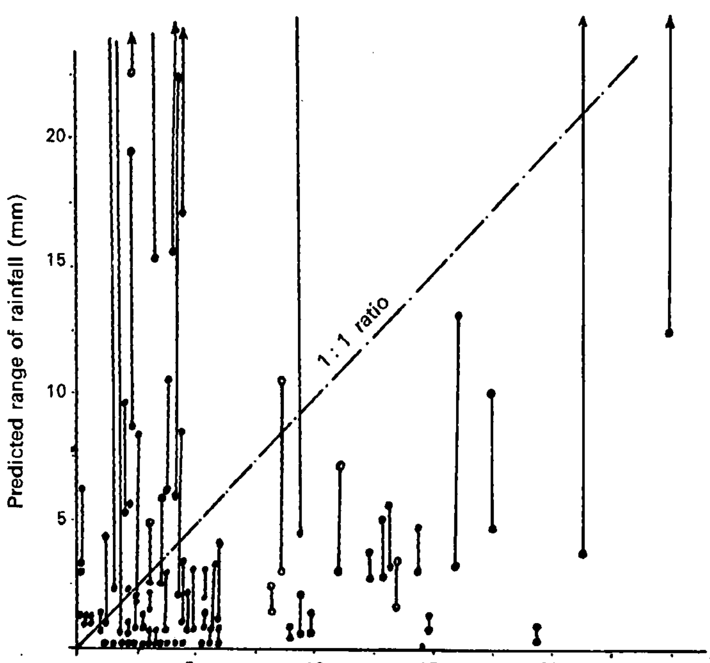

FIGURE 2 Measured rainfall (average for stations in the sugar belt receiving more than 1 mm).

The predicted natural rainfall from the model, for three sizes of cloud, was compared with the rainfall data from 40 rainfall stations in the Natal sugar belt. A scatter diagram (Figure 2) of the predicted range of rainfalls (largest to smallest cloud) against the average rainfall measured from those stations receiving more than 1 mm shows eleven cases ($<10\%$) which pass through the 1 : 1 ratio line, while most of the others are orientated about either axis. The predicted natural rainfall and percentage increase, for the smallest cloud size, due to hygroscopic seeding for all occasions when clouds were present are given in Table 2. In view of the poor agreement shown above (Figure 2), their reliability becomes doubtful.

A similar study, using Simpson's model,[9] was conducted for Natal by Garstang Moskowitz & Tyson.[10] They found that, over a 5 year period, 9,8% of the days were suitable for AgI seeding. However, they concluded that "preliminary but accurate cloud census which provides statistical distribution of cloud heights and diameters is essential if meaningful decisions about cloud seeding are to be made".

(3) Time-dependent model[11]

During January, 1975 a time-dependent, one-dimensional numerical model became available at Nelspruit. Since cloud forming processes are time-dependent this model should be far more realistic than the steady-state case. Unfortunately it has one serious disadvantage, in that it requires approximately six hours of computer running time for a predicted cloud life of one hour and consequently cannot be applied to the same extent as the steady-state case.

The model was checked against radar and raingauge measurements of a storm in the Eastern Transvaal, and indications were that it duplicated the essential details of a storm as well as the measured rainfall. The predicted rainfall, for the case that most closely approached radar measurements, was within 5% of that measured. The results also indicated that the model predictions of rainwater distribution and cloud duration were extremely sensitive to the stability of the sub-cloud layers.

Eight soundings, considered to be typical of the lower atmosphere during the passage of a depression along the Natal coast, were analysed with the model. The results indicated the following:

(*a*) For clouds with their buoyancy forces maximised in the lower third of the cloud, the raindrops would on some occasions not be heavy enough to descend through the resulting high velocity band. The raindrops, in this one-dimensional model, are slowly eroded by entrainment before their combined mass can subdue the updraught sufficiently for fallout to occur. By increasing the coalescence rate, when simulating hygroscopic seeding, the quicker formation of the rain drops enables the water loading to instigate a down draught with resulting precipitation at the ground.

In three-dimensional space, however, this may not be true as an updraught and downdraught may co-exist.

(*b*) All the other solutions investigated showed increases or decreases with seeding of less than 7% which is considered to be negligible.

An attempt to assess the number of occasions with soundings which indicate clouds where the buoyancy forces were maximised near the bottom of the cloud proved extremely difficult, mainly on account of rapid changes in low layer temperatures during the passage of a depression. Twelve soundings were considered to be applicable during the seven months, i.e. approximately 6%. Unfortunately time did not permit model runs on these days and therefore the predicted increases cannot be given.

Summary and conclusions

Frequently the additional amount of rainfall which is economically profitable may be very much smaller than is possible to detect by statistical techniques, even with reasonable amounts of data. It may therefore be appropriate, under such circumstances, to risk the expenditure if there appears to be a reasonable chance of success, even though the likelihood of being able to demonstrate the achievement is small. Conversely, it would appear that a correspondingly small decrease would represent a sizeable economic loss and, therefore, if the probability of an increase is not considerably greater than the probability of a decrease, the expenditure in the cost of an operation is unwarranted.

World-wide experiments have shown that, under certain conditions, cloud seeding can produce significant increases in rainfall, as well as decreases. The conditions for these effects are fairly well established and it therefore remains, in assessing a seeding climatology, to determine the frequency of occurrence of each condition.

The results of the numerical model analysis are inconclusive in determining the number of seedable days that have occurred. This inability to forecast accurately the occurrence and behaviour of clouds in Natal, and therefore the seeding effects on them, stems from the following:

(i) The majority of the coastal clouds are formed from large scale forced ascent of warm, moist air in frontal systems or in passing over surface barriers. Since the numerical analyses rely entirely on clouds developing under localised buoyancy effects they cannot be expected to predict accurately the dimensions and rainfall from large scale effects.

(ii) The majority of convective clouds appear to develop over areas above 1 000 m (Midlands and escarpment) and then, particularly the large clouds, move eastwards towards the coast under the effect of the upper westerly circulation. Those convective clouds that do develop over the coast are usually associated with other effects such as fronts.

(iii) The radiosonde sounding at Durban does not appear to be close enough to the source of many of the convective clouds to be representative of their atmospheric conditions.

(iv) The cloud droplet spectrum, which is usually established within the first hundred metres or so of the cloud base, is not accurately known. Consequently, as this spectrum determines the efficiency of precipitation for a given dynamic system, any suspected alteration by hygroscopic seeding will be purely hypothetical unless the model is correctly "calibrated".

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