Cloud seeding — its effects may linger

A fresh analysis of more than 30 years of Australian rainmaking experiments suggests that cloud seeding may have been much more effective than previously believed.

The analysis, by Dr Keith Bigg of the Cloud Physics Laboratory of the CSIRO Division of Atmospheric Research, has indicated that rainfall increased over areas much larger than the areas actually seeded, and that the increases persisted for weeks and months.

Previously it has been assumed that seeding only affects the target area, and only on the day of seeding. The main reason for this assumption is that light affects the silver iodide used for cloud seeding, deactivating it within a matter of hours. The principle behind cloud seeding is that silver iodide particles act as nuclei around which rain-producing ice crystals can develop in clouds.

Dr Bigg has found that ice nuclei numbers, boosted by cloud seeding, remain at increased levels long after the seeding has stopped. (Why this is so is not at all clear yet.) His analysis of rainfall records for areas used for rainmaking experiments points to corresponding prolonged increases in precipitation.

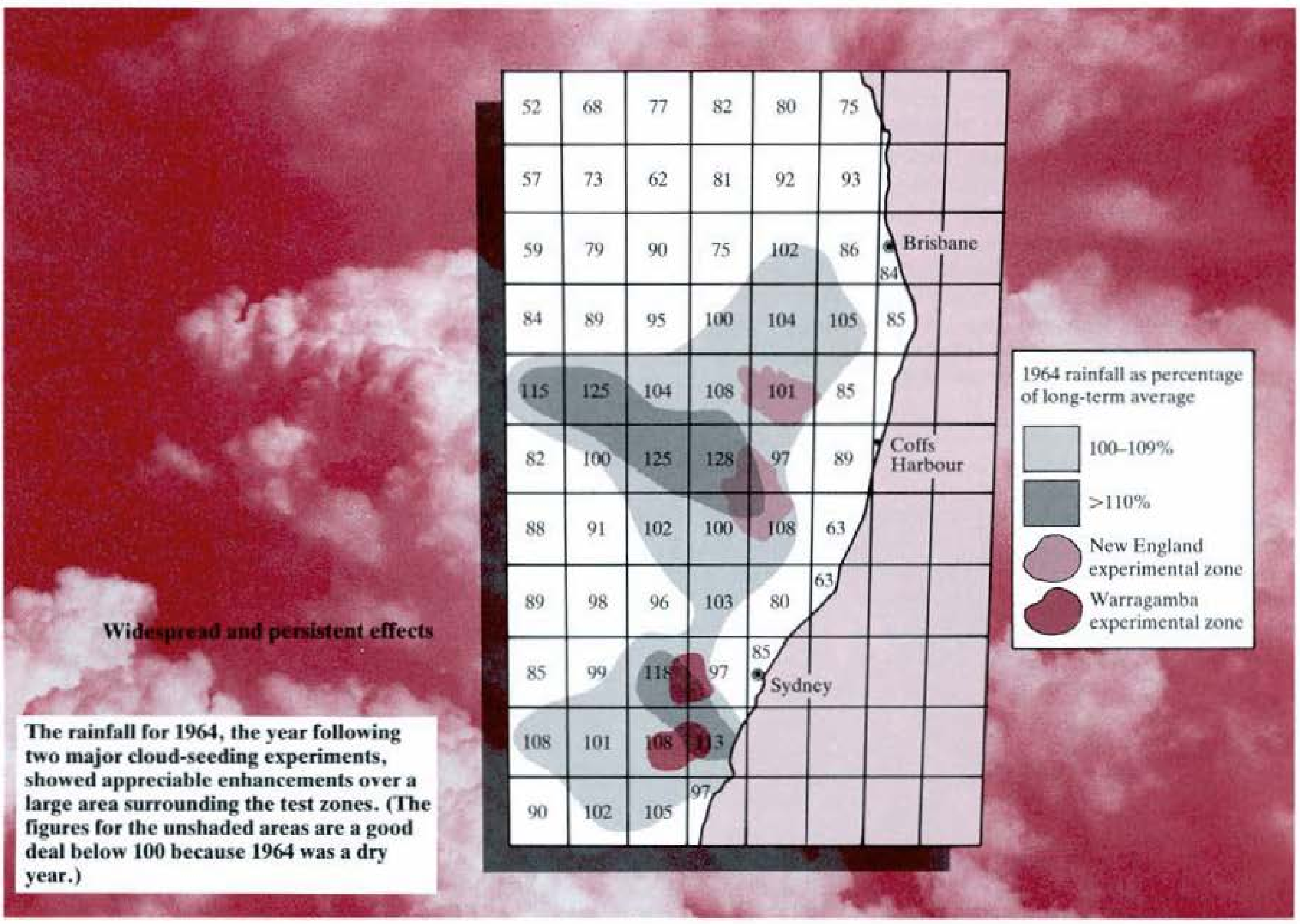
The explanation for the failure to recognize such increases before is that the unseeded 'control' areas used in the experiments were themselves affected by the cloud seeding. The lingering impact of seeding seems to have increased rainfall over thousands of square kilometres surrounding the seeded 'target' areas, including the control areas.

Dr Bigg, a participant in a number of early cloud-seeding trials, has measured the impact of seeding experiments by examining rainfall records for seeded areas and surrounding regions. The map shows what he found in the regions around the Warragamba and New England areas of New South Wales where cloud-seeding experiments were conducted in 1963. Rainfall in the experimental areas for the following year was consistently higher than in surrounding areas.

Dr Bigg has done a similar analysis for five experiments from 1955 to 1964, and superimposed the maps with the seeded areas at the centre. The resulting pattern, reproduced on page 4, shows rainfall increases exceeding that in the central square by more than 10% in an area at least 10 times that of the target. Seeding evidently has had a greater effect east and west of the target square than in the target itself.

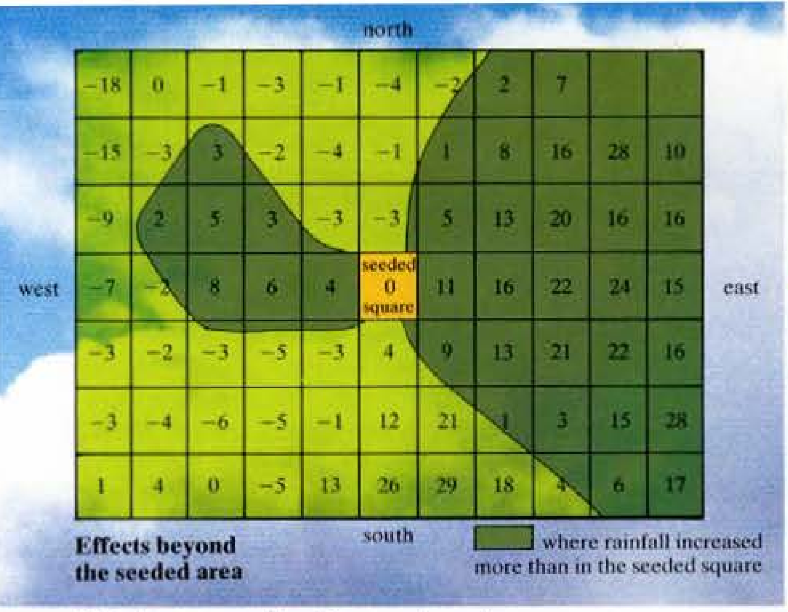
Taking such persistent and widespread effects into account can turn 'failed' rainmaking experiments into successes.

For example, rainmaking experiments in New England from 1958 to '63 (judged at the time to have returned a meagre 4% rainfall increase) can be reinterpreted as resulting in rainfall increases of 19% on the day of seeding (or perhaps 36% if the control area were affected too on the first day), 10–14% increases for 1 to 10 days after seeding, and 3–8% for the subsequent period extending to day 50. A highly successful operation!

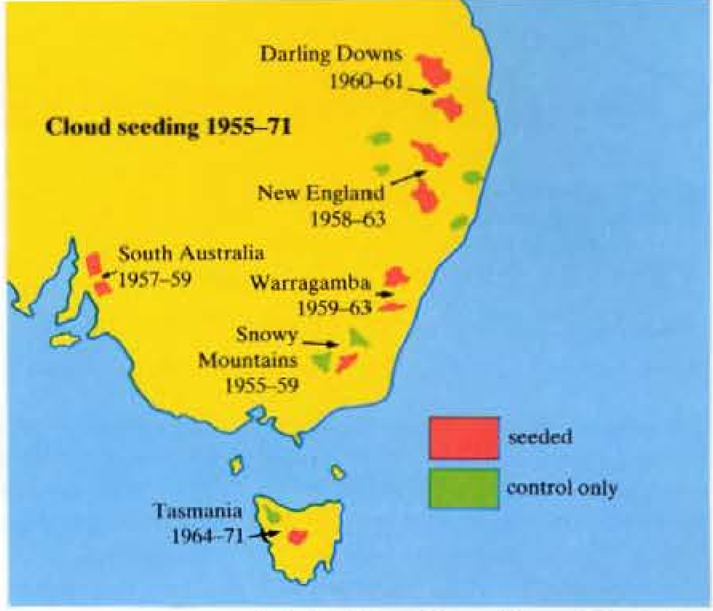


Widespread and persistent effects

The rainfall for 1964, the year following two major cloud-seeding experiments, showed appreciable enhancements over a large area surrounding the test zones. (The figures for the unshaded areas are a good deal below 100 because 1964 was a dry year.)



This diagram, produced by superimposing five grids derived in a similar way to the one on page 3, suggests that Australian rainmaking experiments in the 1950s and '60s had a greater effect west, and particularly east, of the seeded areas than in them. Each grid represented a 5-month experimental period. The averaged rainfall figure for the seeded square was 110% of the long-term average; Dr Bigg derived the number in each square by subtracting 110 from the equivalent figure for that square. (The positive figures south of the seeded square do not represent real increases but are an artificial product of the use of 'twin' seeding areas in most experiments.)



Only the Tasmanian and Snowy Mountains experiments used a single target. The others were of the 'cross-over' type and used a target randomly selected from two sites, although the New England experiment also had consistent controls.

The 'failure' came about because about every 12 days the cloud seeders would re-designate an area as 'target' or 'control' according to a prearranged random schedule. (Sometimes additional 'control only' areas were used.) Because they assumed that the effects of seeding did not persist, they thought the same areas could safely be used alternately as target and control. Now it appears that seeding caused a persistent increase in rainfall in the whole experimental region, making rainfall comparisons between the target and control areas meaningless.

Three other such 'cross-over' experiments (localities shown on the map) were conducted between 1957 and 1963. In the Warragamba experiment, daily selection of target and control areas was made. Results were consistently disappointing.

Consistent targets

Two other experiments, in the Snowy Mountains and Tasmania, used a consistent target and control. These two achieved degrees of success showing statistical significance. The first returned a promising 19% increase in precipitation, and the second highly significant increases of up to 40% in autumn, less in winter, and none in spring (there was relatively little seeding in summer, as few susceptible clouds came by).

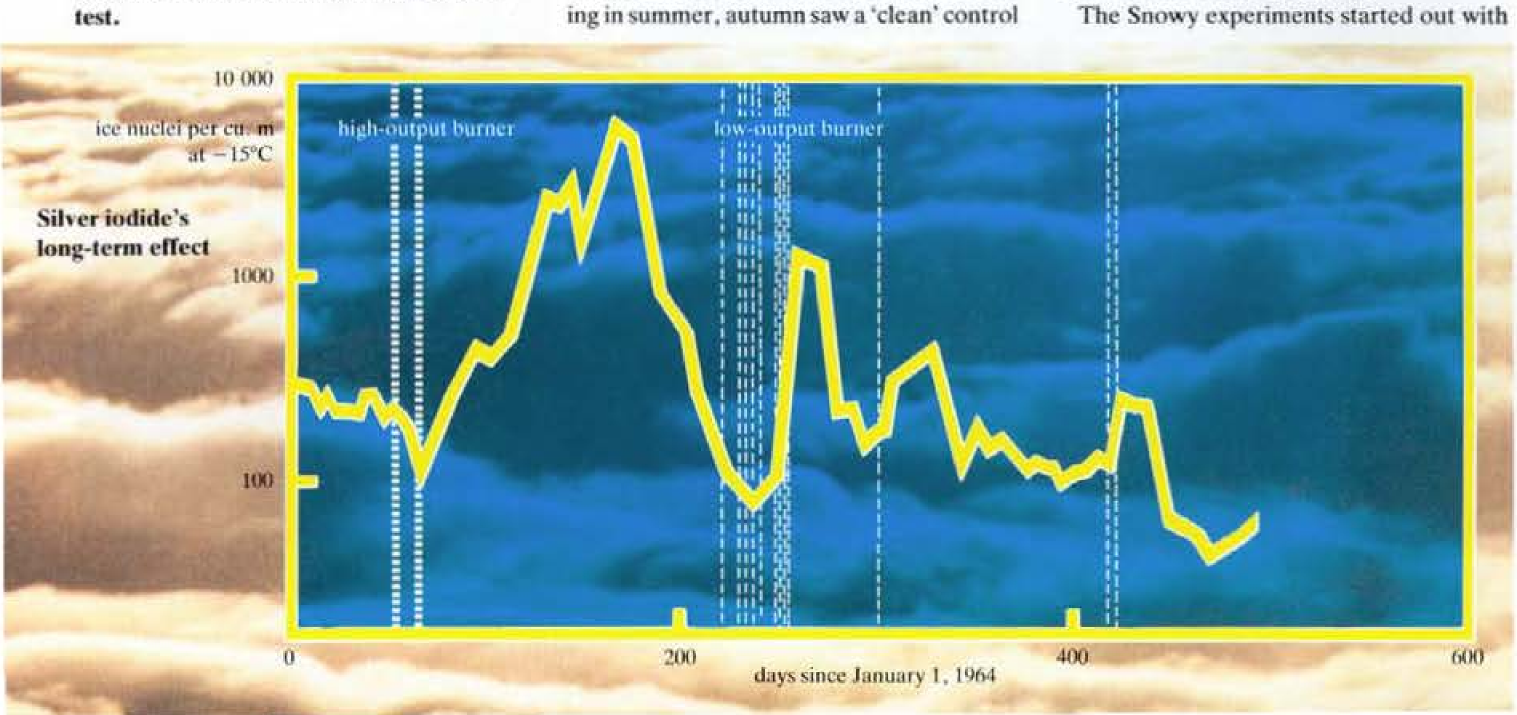
With hindsight, we can appreciate that the Tasmanian result displays a systematic effect explainable by a spreading influence on the control area. With virtually no seeding in summer, autumn saw a 'clean' control area, which became increasingly affected during winter and spring.

In both these experiments the control areas apparently became progressively 'contaminated', and during unseeded periods both target and control became permanently affected. Both factors mean that the magnitude and extent of the effects of cloud seeding may have been grossly underestimated. The Snowy Mountains result was probably much higher than 19%, and the Tasmanian autumn figure could fairly be applied to winter and spring as well.

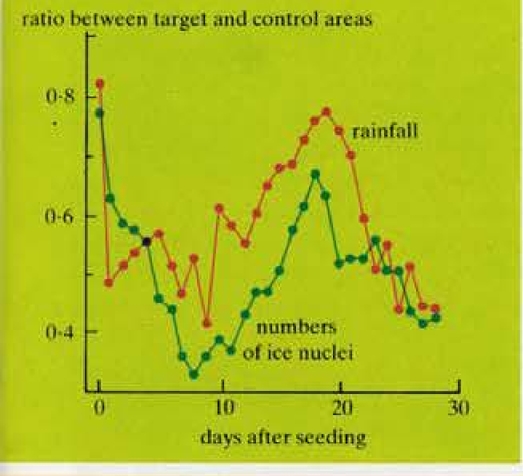
In fact, all the cloud-seeding experiments gave results that, on average, seemed to deteriorate as the operation progressed. In New England, the experiment had a successful first year, but by the end of the sixth year virtually the same amount of rain fell in seeded and control areas. Warragamba also showed a decline with time until, at the conclusion of the fourth year, target rainfall equalled the control-area falls.

The Snowy experiments started out with

Ground-based testing of high- and low-output silver iodide burners was carried out near Sydney in 1964–65 (dashed lines indicate dates). Ice nuclei numbers 8 km away rose sharply and stayed at increased levels for some time after each test.



Rainfall and ice nuclei numbers



30% increases in the first year and ended with a paltry 3% in the fifth. Interestingly, after the fourth year the decline with time was noted, and was suspected to be due to insufficient seeding. So the scientists made a special effort to step up seeding in the fifth year. Possibly a year off would have been a better solution.

All this suggests that the effects persist over years! Consequently, experiments

Rainfall and the abundance of ice nuclei correlated well. These data come from Tasmanian experiments between 1964 and 1970.

crossing over every couple of weeks are going to impart very little influence on top of this major long-term trend.

In 1966 Dr Taffy Bowen, then Chief of the CSIRO Division of Radiophysics and in charge of the rainmaking research, suggested that seeding created cumulative and persistent effects. The problem was that nobody could identify any physical mechanism that could produce such a result.

Dr Bowen supposed that a positive feedback effect was created: the extra precipitation caused by seeding led to increased soil

Ice nuclei and rain

The problem a cloud faces in producing rain is that it has a limited lifetime, maybe half an hour to an hour for one particular cloud cell (sections of clouds are constantly dissolving and reforming). Somehow in that time it has to create drops a million times the volume of an individual cloud droplet if rain is to fall. Ice crystals are the key to this process, but they aren't as easy to come by as you would think.

Particles that act as nuclei for ice crystals are relatively rare. Of millions of airborne particles, perhaps only one will have those special properties that allow an ice crystal to form at temperatures just below freezing. Unless those ice nuclei are present, water vapour will form super-cooled water droplets instead. However, as the temperature becomes lower, we find that matters improve, and at −30°C perhaps one particle in a thousand will act as an ice nucleus.

Ice crystals can grow at the expense of super-cooled water drops. They get bigger and bigger until they shatter into fragments that act as secondary nuclei, or they melt and fall as raindrops. One to ten crystals per litre of cloud is enough to start the rain-making process.

On the other hand, it is possible to have clouds composed entirely of ice crystals, but still no rain comes from them. An optimum number of ice crystals is needed: not too few, and not too many.

Since many potentially rain-producing clouds lack crystals, the idea behind cloud seeding is to add a substance that makes up for a general lack of primary ice nuclei, and hence promotes rain. Silver iodide, one of the photographic chemicals, is the material most commonly used.

To provide ice nuclei, a material must have a molecular spacing that acts as a template for ice crystals. Silver iodide has this special and unusual property, but what constitutes natural ice nuclei remains largely unknown.

Strange as it may sound, it is becoming clearer that bacteria seem to comprise a large fraction of ice nuclei in nature. Scientists have found that certain clay particles also do the trick, but this could be because they carry soil-living bacteria.

Forty years ago it looked as though, simply by adding ice nuclei to cold clouds, we could increase rain almost at will. Trials conducted during the 1950s and early '60s demonstrated that seeding could increase the amount of rain deposited by individual clouds by a factor as large as three or four. However, proving that the process works over large areas is more difficult, as the main article makes clear.

Experiment followed experiment, and the early optimism faded. The last CSIRO work, conducted in Victoria's Wimmera district in 1979–80, came up with the conclusion that there were almost no occasions when seeding could be expected to work (see *Ecos* 32). This showed that clouds worth seeding must have a water droplet content of more than 0·1mg per L, contain few ice crystals (less than 10 per L), and be colder than −8°C — an extremely rare combination of circumstances.

And so the concept of inducing rain by adding ice nuclei is a big simplification. Nevertheless, as Dr Bigg has found, there does appear to be a fair degree of correlation between ice nuclei numbers and rainfall.

Dr Bigg doesn't want to see a repetition of the '60s, when orchardists in the Huon Valley purchased and released large numbers of 'hail-prevention rockets' — with exploding silver iodide warheads. Goodness knows whether they worked, but they probably put more silver iodide into the atmosphere on a few days than was used in a year of cloud-seeding experiments.

If any more cloud seeding is done, it needs to be approached carefully and deliberately. In 1983, experiments run by the Tasmanian Hydroelectric Commission showed a very substantial increase in precipitation on seeded days. If widespread and persistent effects of seeding are confirmed, those undertaking seeding will be faced with very difficult decisions as they attempt to take into account the interests of everyone affected.

Seeding effects cannot be simply switched off, so are we willing to tolerate higher falls of rain beyond the growing season and into harvest time? Does the prevalence of hail increase? Does the alteration in microbiology affect the incidence of plant diseases? Should we do it at all; and who makes the decision?

Optimistic days.

Participants in a 1965 CSIRO cloud seeding school are shown how silver iodide burners work. New findings suggest that ground-operated burners may be as effective as airborne ones.

moisture, which might make natural rain more likely subsequently. Recent studies of rainfall in large irrigated areas tend to suggest that some such feedback can occur, in that irrigation creates small climatic anomalies that persist when the irrigation stops.

Ice nuclei

However, Dr Bigg believes that the explanation for cloud seeding's persisting impact will be found by studying its effect on ice nuclei. He has been in the business of studying the abundance and make-up of these nuclei for many years, and has compiled a lot of data on how cloud seeding affects their numbers.

In three of the areas used for rainmaking experiments, Dr Bigg made measurements on ice nuclei during the experiments and continued them for 4–36 months after seeding stopped. These valuable data, which he has only recently returned to and re-evaluated, show that natural ice nuclei concentrations are greatly increased by cloud seeding, and that the effects last for long times.

Examining a number of cloud-seeding experiments, he finds that the ratio of ice nuclei numbers above the target to those above control areas reflects quite well the ratio of rain amounts in these two areas. The graph at the top of page 5 shows the close parallel measured in one group of experiments.

In some areas seeding had its greatest effect on nuclei numbers within a week or two; in others it took about 11 weeks to reach maximum impact. In all cases, when it ceased in an area subject to prolonged seeding, the decline in ice nuclei numbers continued for at least a year afterwards.

The graph on page 4 shows how very large enhancements of ice nuclei followed the release of silver iodide in one case. Enhancement persisted for long periods. The data came from Dr Bigg's monitoring of ice nuclei numbers at a spot 8 km away from where other scientists happened to be carrying out ground tests of silver iodide burners before fitting them to aircraft.

Seeding index

The graph suggests that the effect of seeding is a large build-up in ice nuclei numbers — followed by a decay. Dr Bigg attempted to model this mathematically by constructing a cumulative 'seeding index' that reflected such behaviour. Each kilogram of silver iodide released in an area adds to the index, which then decays exponentially with time — until the next seeding episode — and so on.

In two cases he has had startling success in relating an area's cumulative seeding index to the enhancement of its rainfall (compared with that in control areas). The results of the New England experiment, given in the adjacent graph, show a three-fold rainfall enhancement as the index varies from zero (no seeding) to the figure reflecting maximum cloud-seeding effect.

But, how is it possible for the effects of seeding to persist for many months?

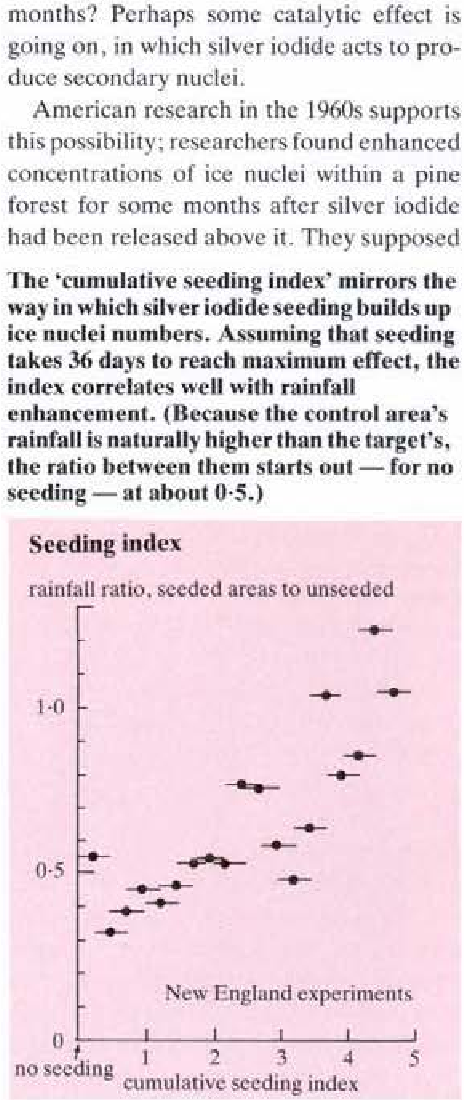
Dr Bigg calculates that aerial cloud-seeding experiments typically deposited only about 0·01 mg of silver iodide on each square metre of ground in the target area each year. Moreover, the silver iodide, while released as crystals, would be washed down with the rain and arrive on the ground in solution. And, although plants would retain a fraction on their leaves, most would end up in surface soil. It seems most unlikely that enough silver iodide, as crystals, could be released back to the air to have an effect, especially when we recall that the molecule splits up under the influence of light.

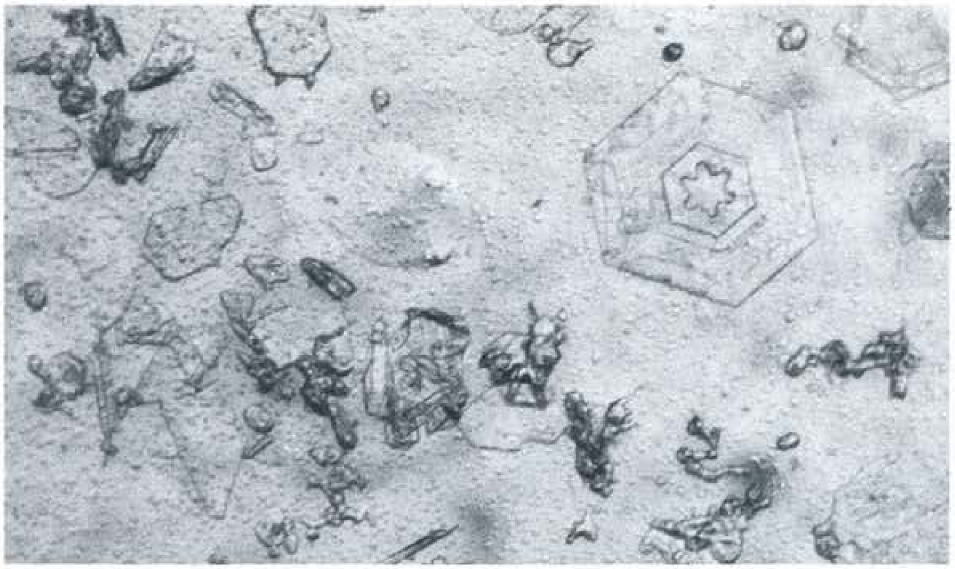
Silver on its own doesn't appear to have any ice-nucleating properties and, besides, a cloud-seeding experiment adds about as much silver to the target-area soil as is naturally present in topsoil. Iodine by itself has some ice-nucleating ability, but only in high concentrations (in small quantities it evaporates to a gas). In any case, iodine occurs naturally in soil in much greater quantities than are added artificially.

So how could minute amounts of silver iodide solution within the soil lead to an increase in ice nuclei numbers lasting for months? Perhaps some catalytic effect is going on, in which silver iodide acts to produce secondary nuclei.

American research in the 1960s supports this possibility; researchers found enhanced concentrations of ice nuclei within a pine forest for some months after silver iodide had been released above it. They supposed

The 'cumulative seeding index' mirrors the way in which silver iodide seeding builds up ice nuclei numbers. Assuming that seeding takes 36 days to reach maximum effect, the index correlates well with rainfall enhancement. (Because the control area's rainfall is naturally higher than the target's, the ratio between them starts out — for no seeding — at about 0·5.)





A cloud's ice crystals under the microscope — bacteria may be the nuclei of many.

that the chemical somehow reacted with the pines' essential oils, slowly releasing secondary ice nuclei.

Dr Bigg puts forward a more radical hypothesis: he suggests that silver iodide causes certain bacteria to develop outer layers that promote ice-crystal formation.

Bacteria cause rain?

Most substances that act as efficient ice nuclei have surface regularities that match the lattice spacing of ice crystals. Within the last 10 years scientists have come to appreciate that common plant- and soil-living bacteria possess this property — and, more significantly, that many natural ice nuclei are actually bacteria.

You notice that frost forms on grass whenever the temperature falls below freezing point. Yet, remarkably, if you sterilize a leaf surface and place it in a cold chamber, frost will fail to form until temperatures fall below −20°C! It's bacteria that make the difference.

In the United States, soil bacteria are added to snow-making machines to improve their performance. Conversely, genetically engineered bacterial clones have been developed that lack ice-nucleating abilities. Sprayed on crops, these replace the natural bacteria and prevent frost damage.

Dr Bigg's suggestion is that trace quantities of silver iodide taken up by a host plant (either directly on the leaf surface or through the roots) can increase the numbers of bacteria that have the right molecular regularities on their outer coat for initiating the growth of ice crystals. He is currently testing the idea in his back yard, where he has set up two covered plots, one watered with a silver iodide solution, the other not. He is measuring the numbers of ice nuclei liberated from each plot.

In an interesting recent experiment, a pair of scientists at the University of Alaska cultured ice-nucleating bacteria in the laboratory and found that successive generations lost their ice-nucleating ability. Perhaps, if they are to retain their ice-nucleating capacities, bacteria need to take up trace quantities of substances such as silver iodide.

Dr Bigg thinks a process in which silver iodide acts as a catalyst is the most likely explanation for the persistent effects of cloud seeding. However, it is not the only possibility. One species of bacterium with ice-nucleating properties is known to be dispersed most effectively during wet and windy conditions. Perhaps a simple positive feedback effect is at work, whereby a single successful cloud-seeding event leads to conditions more conducive to the reproduction and dispersal of ice-nucleating bacteria.

Whatever the reason for the effect, it casts considerable doubt on the conventional understanding of cloud seeding. Its effects appear to persist much longer than the 24 hours that has always been assumed to be a reasonable maximum.

And if that is so, the estimates of an experiment's success have been incorrect, and more rain may have been produced than hitherto thought.

Andrew Bell

So what will happen now?

Dr Bigg's results are scientifically intriguing and — if further work shows that his conclusions are correct — potentially of great significance to dry countries such as Australia, comments Dr Neville Fletcher, Director of CSIRO's Institute of Physical Sciences. Dr Fletcher makes the following points.

▷ Conclusions based on statistical data collected for another purpose are notoriously unreliable. However, if Dr Bigg's conclusions are correct, similar persistence effects should show up in most of the cloud seeding experiments that have been conducted around the world during the past 20 years. I hope our overseas colleagues will now search the records of their experiments to look for this effect.

▷ Dr Bigg has suggested a mechanism that may account for the persistence of seeding effects, which he is now investigating further. Some working hypothesis with a reasonable amount of experimental support is necessary before the next step can be planned.

▷ If further statistical support for Dr Bigg's conclusions emerges and if the mechanism responsible can be understood to a reasonable degree, then it would be possible to devise a seeding experiment to test the theory in more detail. On the basis of Dr Bigg's present model, the silver iodide would probably be dispersed from generators on the ground rather than from aircraft. Because of the long persistence times involved, the experiment would probably have to run for at least 10 years to produce a reliable conclusion.

▷ Because of the long time and large investment required, no such experiment could be properly planned until the underlying mechanism is better understood. Generally, once a field experiment has commenced it cannot be altered without wasting all the time and effort already invested in it.

More about the topic

Unexpected effects of cloud seeding with silver iodide. E.K. Bigg. *Journal of Weather Modification*, 1985, **16** (in press).

Estimating cloud-seeding success in the presence of persistent effects of seeding. E.K. Bigg. *Proceedings, Fourth W.M.O. International Weather Modification Conference, Hawaii, August 1985.*

Persistent effects of cloud seeding. E.K. Bigg. *Search*, 1985, **16**, 40–2.

Why CSIRO has stopped cloud-seeding. *Ecos* No. 32, 1982, 23–5.

What are the best clouds to seed? *Ecos* No. 24, 1980, 18–19.

Rainmaking: the state of the art. *Ecos* No. 16, 1978, 15–18.