ADVICE ON THE IMPACT OF POLLUTION ON RAINFALL AND THE POTENTIAL BENEFITS OF CLOUD SEEDING

A report to

The Secretary
Australian Government Department of the Environment and Heritage

By

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5 December 2002

CONTENTS

TERMS OF REFERENCE

The consultant will provide advice to the Secretary, Australian Government Department of the Environment and Heritage, on the scientific basis of the claims by Mr Aron Gingis on the role of air pollution in decreasing rainfall in areas of SE Australia and on the potential for cloud seeding to reverse the decrease.

In formulating this advice the consultant will briefly review the international scientific literature, gather information by e-mail from leading scientists in the field, within Australia and overseas and, on the basis of the information so gathered, indicate whether there is sufficient evidence to support Mr Gingis' claims.

[Mr Gingis is Managing Director of Australian Management Consolidated Pty. Ltd., Suite 1, 252 Grange Road, Ormond, Victoria 3204.]

SUMMARY OF CONCLUSIONS

a) Although satellite observations show clear evidence of cloud modification and reduced precipitation in regions downwind from many industrial sites in Australia under certain conditions, it has not been established that this has had any significant effect upon annual precipitation in these regions. Indeed the average annual precipitation in most areas of Southeastern Australia has shown an overall increase over the past 50 to 100 years.

b) Overseas and Australian experience shows that properly designed cloud seeding techniques can perhaps increase precipitation by as much as 10% in some areas, though in other areas the effect may be nearly zero or even negative. While techniques based upon seeding individual clouds appear more efficient than area seeding approaches, they are much more expensive and have not been shown to have a great effect upon rainfall over a large region.

c) Any new plans to try cloud seeding techniques in Australia should first estimate the likely cost/benefit ratio, which will depend upon cloud microstructure conditions in the area, the proposed seeding techniques, and the use to which any additional precipitation is to be put. Any such approach should involve a well designed experimental program that may need to continue for at least five years to reach any significant conclusion. The design, supervision, and evaluation of any such program should be carried out by a scientific committee with representatives from the Bureau of Meteorology and CSIRO, as well as independent scientific experts.

EXECUTIVE SUMMARY

1. Mr Gingis claims that studies made by Professor Daniel Rosenfeld of the Hebrew University of Jerusalem and by his own company have established that annual rainfall in the Snowy Mountains and in the Victorian Alps has been reduced by at least 30 percent over the past 50 years. He identifies the cause of this decrease as being industrial pollution from activities near Adelaide and near Geelong. He further claims that cloud seeding techniques developed by Professor Rosenfeld are able to reverse this effect, and proposes a program of investigation followed by operational seeding, these programs to be carried out by his company.

2. Professor Rosenfeld is well known and respected for the techniques he has developed for deducing cloud properties by satellite observation. These observations do show clear tracks downwind of industrial sites near Adelaide and indicate that cloud properties are affected within the tracks for distances of up to 300 km downwind. Cloud droplets within the affected clouds are smaller than in clouds outside the pollution track and there is evidence that rainfall is inhibited within the track. Similar satellite data was later presented for other locations in Australia. These data are, however, the results of observations on only a few selected days when cloud properties were appropriate, and no long-term observational program has been carried out.

3. Professor Rosenfeld subsequently found apparent evidence in official rainfall records for a decline in rainfall in some areas of the Snowy Mountains and Victorian Alps which he attributed to the effects of these pollution tracks. Investigations by the Bureau of Meteorology, however, showed that these apparent decreases could be accounted for by the closure or relocation of certain observation stations in high-rainfall areas of the districts included in the official area rainfall calculations.

4. Long-term records of Australian rainfall show that there has, in fact, been an increase in rainfall in all areas over the past century, with the exception of a region in Southwest Western Australia where the rainfall has decreased at a statistically significant level, and in Tasmania where the decrease is small and not statistically significant. Rainfall in any given area, however, has large variability on an annual scale, and even when averaged over ten years to give decadal rainfall. Patterns of declining rainfall over periods as long as 20 years can be seen in records as long ago as 1900, but are later compensated for by periods of increasing rainfall.

5. Rainfall records in California show that there is evidence for an inhibiting effect of pollution plumes originating in coastal cities on rainfall in mountain regions downwind from those cities, the distance involved being 50 to 100 km. The rainfall records support, though only weakly, the proposition that the rainfall deficit was remedied by Clean Air legislation in recent decades.

6. It is concluded that there is no reliable evidence that pollution plumes have actually decreased annual rainfall in the Snowy Mountains, in the Victorian Alps,

or in Western Victoria. Some such effect cannot, however, be ruled out and is not unreasonable on physical grounds, but may be minor and limited to certain cloud types and wind trajectories.

7. Theoretical treatments, computer models, and measurements in real clouds show that seeding some clouds with large (1–2 micrometre) salt particles can change their microstructure in a direction favouring later precipitation. This is effective only for clouds with unusually small droplet sizes and can be counterproductive if the natural droplet size is large. Similarly, seeding clouds of large vertical extent with silver iodide can induce ice formation and so enhance precipitation. This is effective only for clouds with very small numbers of natural ice nuclei, and can be counterproductive if the concentration of natural nuclei is large.

8. Irrespective of any influence of industrial pollution, experiments in Australia and overseas have shown that cloud seeding with silver iodide has probably been able to increase rainfall in some mountain regions by about 10 percent. In other regions extensive experiments have failed to produce a clear increase. Controlled experiments must generally be continued for 5 to 10 years to have any hope of giving a statistically significant result. In Australia, long-extended experiments and operations in Tasmania appear to have produced a rainfall increase of about 8% in the target area without adverse effects in either upwind or downwind areas, though evaluation of more recent seeding operations raises questions about the actual increase achieved in the target area. In the Snowy Mountains, long-continued experiments failed to produce a non-controversial result. A carefully designed experiment in Western Victoria was abandoned because suitable cloud-seeding opportunities were too few.

9. The seeding methods used by Professor Rosenfeld and advocated by Mr Gingis are similar to those that have been used over the past fifty years, but operational convenience and efficiency have been refined. In addition, there have been great advances in observational techniques using special instrumentation in satellites and advanced radar techniques. The approach of seeding individual clouds, as is done in Texas, produces apparent striking successes, as was first demonstrated in Australia in the 1950s, but gives little information on the potential of the technique to increase rainfall over a large area, even if carried out on an "operational" basis. There is controversy about the success of both the Texas program and the related long-running program in Israel.

10. Given that any cloud-seeding program capable of producing statistically significant results will need to be conducted over at least five years and will cost many millions of dollars, careful consideration must be given to it in advance. Before deciding on any such program, a careful analysis of cloud statistics in the experimental region should be undertaken to decide whether the proposed cloud-seeding technique is appropriate and has a chance of success. The design and evaluation of any such program should be in the hands of, and under the continuing supervision of, a broadly based scientific committee, involving both the Bureau of Meteorology and CSIRO as well as independent scientists.

11. If a major concern is the effect of industrial pollution on rainfall, it might be much less expensive and more effective to attempt to reduce or modify the effluent at its

source, particularly since in Australia these sources are identified industrial operations such as power stations or smelters. Doubtless the newer operations already have pollution control measures installed on their effluent stacks, but there is always the possibility of increasing the effectiveness of these devices. Consideration might also be given to a controlled experiment in which the effluent is seeded with large condensation nuclei, essentially by spraying sea water into the hot effluent plume, thereby providing at source the hygroscopic nuclei that cloud seeding would later introduce.

I. THE CLAIMS OF MR GINGIS

Mr Gingis has made representations to the Federal Minister for the Environment and Heritage and others concerning the adverse effects of pollution on rainfall in Southeastern Australia and on the potential of cloud seeding to reverse this trend. Mr Gingis' claims, as far as I have been able to establish, are as follows:

1. Observational data show that rainfall in the Snowy Mountains and Victorian Alps has been very significantly reduced over the past fifty years. The estimated reduction in annual rainfall over this period exceeds 30 percent.
2. Atmospheric pollution, specifically that from sources such as smelters, power stations and refineries, can have a severe inhibiting effect on downwind rainfall because of changes caused in cloud microstructure. Such effects are important in Southeastern Australia, particularly in the Snowy Mountains and the Victorian Alps where they have been clearly verified.
3. Cloud seeding strategies of the type favoured by Professor Rosenfeld have the potential to reverse this effect and so to significantly increase rainfall in these areas.
4. He proposes a cloud-seeding program, with the advice of Professor Rosenfeld, firstly to establish the efficacy of cloud seeding in these areas, and secondly as a large-scale operation to increase rainfall.

In e-mail correspondence with Professor Rosenfeld, he referred me to relevant research publications (some of which were also quoted by Mr Gingis). Since experience of the cloud seeding programs in Israel and in Texas is of some relevance to the Australian situation, he also referred me to relevant publications relating to those programs and to Dr Woodley, who has collaborated with him on the Texas experiments.

II. RAINFALL PATTERNS IN AUSTRALIA

It is possible to support almost any assertion about rainfall patterns by selective quotation of rainfall records. It is therefore important that the records used are from stations with a long-term and reliable record. It is also important that the same set of stations is used for the two stages of the comparison if regional rainfall is being considered. The official records of the Bureau of Meteorology provide long sets of data, and the Bureau has identified initially 191 and later 379 stations with high-quality records suitable for examining rainfall trends across Australia over the period 1910 to today (Lavery et al. 1992, 1997). The chief difference is the addition of many stations in the North and Northwest of the continent to the extended set, though the network is also denser everywhere.

Lavery et al. (1997) analysed the large data set for the period 1890 to 1992 to seek any trends in overall Australian rainfall on an annual basis. This analysis is shown in Figure 1 and indicates no overall change. It is true that there was a significant decline of nearly 40% over the period 1975–92, largely because of the very wet years 1973–76, but a very similar trend can be seen for the period 1890–1915, and overall the total Australian rainfall has actually increased by about 10% over the period 1940–

1992. This overall picture is, however, of limited value in the present analysis because of the wide geographic extent of the continent.

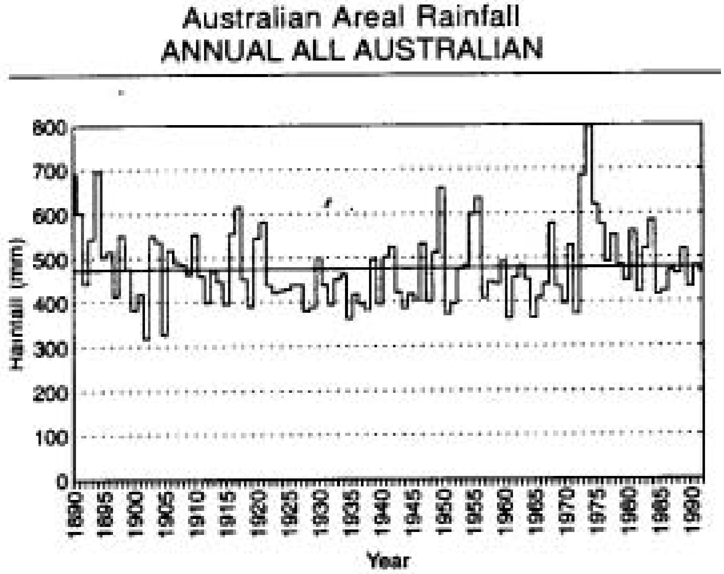

Figure 1. Area-weighted annual rainfall over the whole of Australia for the large data set (Lavery et al. 1997). The solid line shows the trend, which has zero slope.

Nicholls and Lavery (1992) analysed the original smaller data set in 1992 and extracted rainfall trends for many regions of Australia over which consistent patterns emerged following statistical analysis. Since areas showing similar trends were found to be closely grouped geographically, the analysis indicates changes both in total rainfall and in its geographical distribution. Figure 2 shows the rainfall record for Canary Island in Western Victoria (35°58′S, 143°51′E) which is representative of that area. It is clear that there is a variation of about ±30% in annual rainfall, and that even the 11-year running average shows very significant variation. Certainly the average rainfall has declined by about 10% over the period 1950-1990, but the overall trend since 1910 has been slightly (though perhaps not significantly) upward. It is also clear that there are long-term drifts in annual rainfall over periods of 10 to 20 years. One of the most notable features at this location is the large rise in rainfall between 1940 and 1955. This increase occurred over much of Australia, as also did the peak around 1975 shown in Figure 1.

The published record (Nicholls and Lavery 1992) for the reliable station at Brownlow Post Office (34°15′S, 139°16′E), to the West of the industrial sites near Adelaide, does show a small decrease over the period 1910–86, caused mainly by a more extreme version of the general Australia-wide downtrend for the period 1975–86. This could be interpreted as giving support to the pollution hypothesis, except for the fact that the rainfall then recovers over the period 1985–93, with a large peak (636 mm) in 1992 that remedies the apparent downward trend, as shown in Figure 3. This station closed in 1994. A complete record for the neighbouring reliable station of Eudunda (34°11′S, 139°05′E), which has a closely correlated record, indicates a generally slightly rising trend from 1880 to 2001.

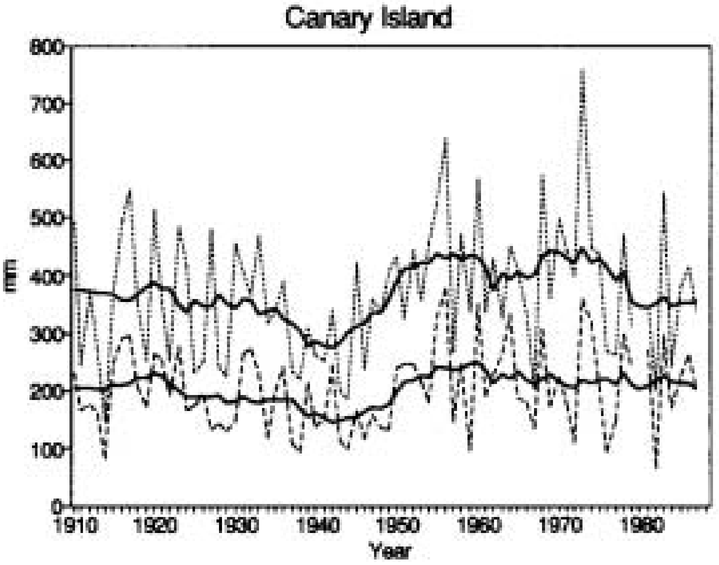

Figure 2. Winter (dashed line) and 12-month (dotted line) rainfalls at Canary Island in Western Victoria for the period 1910-1988. Thick solid lines are 11-point running means of the original curves. Summer rainfall can be evaluated by taking the difference between the two curves (Nicholls and Lavery 1992).

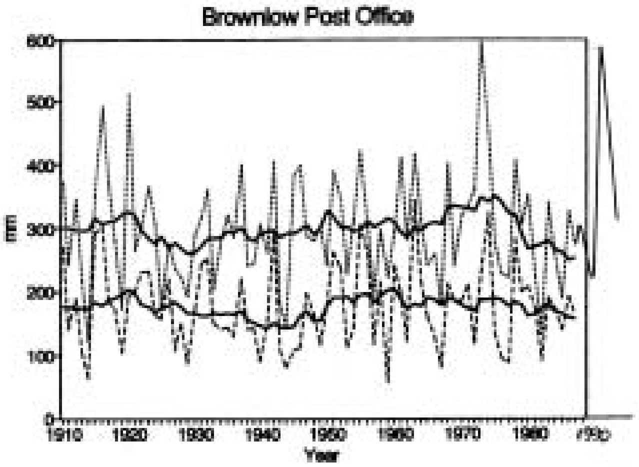

Figure 3. Annual rainfall record 1910–1986 for Brownlow PO, downwind from and close to Adelaide (Nicholls and Lavery 1992), extended with new data to 1994. (The smoothed trend has not been extended or modified, but now rises after 1982.)

An independent analysis of Australian rainfall over the period 1910-1995 was carried out by Hennessy et al. (1999) using the large data set. As well as indicating a small Australia-wide increase (which is not significant however at the 5% confidence level), the data is presented in a manner showing variation between States, as shown in Figure 4. South Australia, Victoria and New South Wales all show positive trends over that time, the trend for Victoria (+15%) being the most statistically significant, though the positive trend in New South Wales is actually larger. Interestingly, there is a strong and statistically significant negative trend for Southwest Western Australia and a much smaller and statistically less significant decrease in Tasmania. A similar analysis is presented rather differently by Suppiah and Hennessy (1998). A further different analysis by Plummer et al. (1999) shows that over this period the area of Australia experiencing extreme wet conditions has risen slightly and the area experiencing extreme dry conditions has fallen slightly, but these trends are not statistically significant because of the extreme interannual variability.

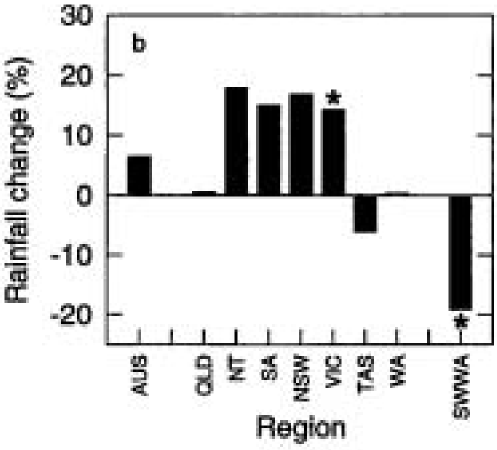

Figure 4. Change in annual total rainfall (from a linear regression) over the period 1910 to 1995 for the whole of Australia (AUS), individual States and Territories, and the anomalous region of Southwest Western Australia. Bars marked with an asterisk are significant at the 5% level (Hennessy et al 1999).

As well as Western Victoria and Western NSW, the Snowy Mountains area is also of prime concern to this report. Mr Gingis claims that there has been a reduction in rainfall in this area of over 30% during the past 50 years. He does not provide the data upon which this statement is based, but it is presumably the District Annual Rainfall (DAR) statistics, which have been compiled by the Bureau of Meteorology since early in the twentieth century. While the DAR figures can give a reliable result for districts in which all rainfall measuring stations have been stable in location and operation, there is clearly a problem if there has been a significant shift in these parameters. This matter has been investigated in detail by Nicholls (2000). The DAR for the Snowy Mountains area, shown in Figure 5, is a composite of many stations, some of which operated for only part of the record time. However Nicholls was able to reconstruct a record with excellent correlation to the original using seven stations with long records. This composite DAR agrees in showing a fairly steady decline in rainfall amounting to about 12% between 1913 and 1995, as shown in Figure 5.

Nicholls, however, has identified the fact that two important high-altitude high-rainfall stations have incomplete records, Kiandra Chalet running from 1866 to 1974 and Guthega Power Station from 1952 to the present. Where they overlap, the records are well correlated, and it has therefore proved possible to produce a composite record for the whole time period. When this is done, the long-term downward trend almost disappears. As shown in Figure 6, the individual stations in the area do not show any significant trend, and the two high-rainfall stations with incomplete records match well together.

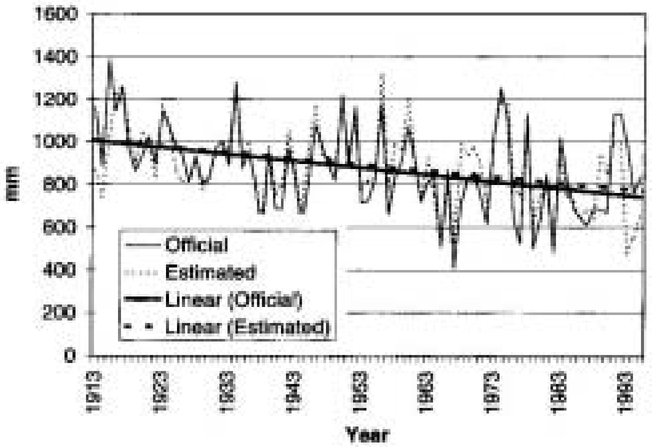

Figure 5. Official Snowy Mountains (District-71) annual District Average Rainfall (DAR) (thin continuous line) with linear trend (thick continuous line). Annual DAR estimated from seven representative stations (thin broken line) with linear trend (thick broken line) (Nicholls 2000). Agreement between the two data series is clearly good.

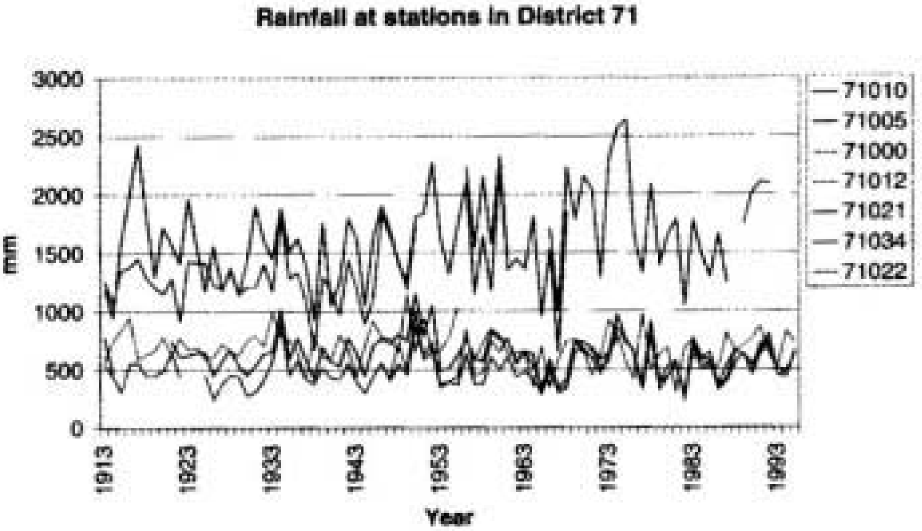

Figure 6. Rainfall records for the seven stations used in reconstructing the district rainfall record. The two high-rainfall stations with incomplete records are clearly evident at the top of the figure. Some of the lower rainfall stations also have incomplete records but these do not have such a great effect on the average.

It is, of course, possible that selection of different stations might produce a rather different result, but the evidence does strongly indicate that simple reliance upon District Annual Rainfall figures can be misleading in areas where there have been significant interruptions in the record, and does provide a fairly convincing explanation of the apparent deviation of the rainfall trend in the Snowy Mountains from that in surrounding areas. It might be argued that there is a significant decrease in rainfall at the high rainfall stations in the period 1973-86, but this is largely the result of unusually high rainfall in 1973-74, which repeats the situation shown for these stations in 1915-30, as remarked more generally before, and is mirrored in the overall Australian rainfall as shown in Figure 1.

E-mail discussions with Professor Rosenfeld on this matter indicate that he identified a significant downturn in rainfall in the Snowy Mountains, relying upon the standard DAR records and others provided by the Bureau. In discussing this with the Bureau of Meteorology, however, the reliability of these records was queried and Dr Nicholls showed that the District–71 rainfall decline could in fact be explained by lack of continuity in the record, as discussed above.

Conclusions

It is not clear upon what evidence claims of a severe decrease in rainfall over the Snowy Mountains and Victorian Alps are based. Given the large inter-annual variability in total rainfall in Australia, as indicated in the Snowy Mountain record of Figures 5 and 6, it is always possible to select decade-scale time windows over which the trend is markedly positive or markedly negative, this being largely correlated to global-scale climate shifts such as those associated with the El Niño – Southern Oscillation (ENSO).

The available evidence on rainfall patterns in Australia strongly suggests that there has been an overall slight increase in annual rainfall in most areas over the past century. (Professor Karoly, as a scientist independent of the Bureau, agrees with this assessment.) The annual deviations from the trend line are, however, very large. Even when smoothed over a decade, there are still deviations of ±10–20% in many places. Although there has been a significant decline in rainfall in some places over the past 25 years, this is not unusual and has occurred many times before. While an effect due to human activities cannot be ruled out, the available evidence suggests that the observed changes in rainfall can be accounted for by natural variations in climatic parameters. From the available information there does not appear to be justification for the assertion that there is a large region of depleted rainfall to the East of industrial sites in Victoria or South Australia, whatever short-term satellite studies might indicate about cloud patterns.

III. POSSIBLE EFFECTS OF ATMOSPHERIC POLLUTION

Cloud Physics

The physics and chemistry of clouds and rainfall have been studied for a very long time, but there have been great advances in the past century, both in the large-scale sciences of climatology and meteorology and in the smaller scales of cloud dynamics and microphysics (Fletcher 1962). Atmospheric pollution, whether from human activities or from expanding deserts, can have significant influences at both these scales (Rotstayn 1999). The discussion here will be concerned with only the smaller scales.

Cloud droplets form when moist air rises above the condensation level, and these droplets form on condensation nuclei, which are generally small solid particles (aerosols) containing soluble materials. Examples of such nuclei are smoke particles, soil particles, and sea salt from spray. Since the amount of condensable water per unit volume depends only upon humidity and temperature, the size of the cloud droplets will depend upon the number of condensation nuclei that are activated, and thus upon the number and type of condensation nuclei. Clouds forming over the ocean, where the air is clear except for large salt nuclei, may have as few as 50 droplets per cm^3 while in drought times the concentration of droplets in continental clouds can approach 1000 per cm^3. Very small droplets do not collide with each other, and move out of the way of larger droplets, so that they cannot coalesce to form rain drops, while for larger droplets this coalescence occurs much more readily. Large concentrations of very small droplets can therefore inhibit rainfall.

Rain can also be formed through the generation of ice crystals in cloud tops. Small water droplets do not freeze readily, and indeed ideally pure droplets do not freeze until the temperature falls to –41°C. The presence of small solid particles, called freezing nuclei, in the droplets can however cause freezing at warmer temperatures. One of the best known freezing nucleus materials is silver iodide (AgI) which can nucleate freezing at about –4°C if its particles are large, and more typically at temperatures around –10°C. Once an ice crystal has formed in a cloud of supercooled water droplets, it grows rapidly since ice is the stable form of water at temperatures below freezing. The growing ice crystals fall through the cloud and collect water droplets by collisions. They melt when they reach the lower parts of the cloud, where the temperature is above freezing, and fall as rain.

Both these rain production processes have other larger-scale aspects to them. In the first place, clouds reflect sunlight falling on their tops, and clouds with many small droplets reflect more efficiently than clouds with fewer and larger droplets. This can affect the total thermal balance of the cloud and thus the rate at which it grows. Secondly, the growth of water droplets, and even more so of ice crystals, releases latent heat which warms the air and causes it to ascend more rapidly. This in turn affects the total height of the cloud and the likelihood of it producing rain.

The effects of pollution

Addition of small aerosol particles, whether from industrial smokes, bushfires, or soil dust, generally contributes small condensation nuclei and these increase the droplet concentration in the clouds, with a corresponding decrease in droplet diameter. It is quite likely that this can have an inhibiting effect on rainfall from those clouds that rely upon droplet coalescence rather than ice nucleation to produce rain. Addition of highly efficient larger aerosol particles however, typically soluble particles greater than 1μm in diameter, can cause preferential droplet nucleation on these particles and actually lead to enhanced coalescence and production of rain. It is just this process that leads to the eventual clarification of air over the oceans. Similarly, the addition of particles that are able to act as freezing nuclei may enhance precipitation from cumulus clouds that grow high enough for their top temperature to be less than about –10°C. The total effect of added atmospheric aerosols therefore depends both on the materials and upon the general structure of the clouds to which they are added. Professor Vali of the University of Wyoming, for example, quotes evidence of emissions from a copper smelter in Spain acting as efficient ice nuclei (personal communication).

Observation of pollution plumes in Australia

An inhibiting effect upon rainfall of smoke from sugar-cane burning in Queensland was noted some fifty years ago by Sean Twomey and Jack Warner of CSIRO, and analysed in these terms. More recently Professor Rosenfeld has developed sophisticated methods of studying clouds from satellites that allow much more detail to be obtained about their microphysical properties (Rosenfeld and Gutman 1994), though the quantitative relation to rainfall is a matter of indirect inference. Essentially the satellite measurements give the reflected intensity of sunlight at various wavelengths, and from this can be deduced something about the average size and concentration of cloud droplets, generally on the assumption of a log-normal size distribution. It has been found that thick clouds with a retrieved average droplet radius greater than about 14μm correspond to areas where there is a strong radar echo, indicating the formation of raindrop-sized droplets within the cloud. This result is consistent with microphysical studies indicating the necessity for droplet radii to exceed 12μm if any coalescence is to occur.

Satellite measurements of stratus cloud over various parts of Europe, Canada and Western Victoria by Rosenfeld (2000) show strong pollution tracks in the cloud-top structure, indicating reduced droplet sizes. In the case of the Australian study, interest centred on the region downwind from Adelaide where smoke plumes from the Port Augusta power plant, the Port Pirie lead smelter, nearby oil refineries, and other industrial plants release large quantities of sub-micron particles into the atmosphere. Each of these sources did in fact produce a clear downwind track of cloud with smaller droplet size extending for several hundred kilometres. One particular overpass of the TRMM satellite was selected for analysis and showed clear evidence of suppression of cloud-drop coalescence and rainfall in the downwind pollution track, while neighbouring clouds showed both coalescence to larger droplet sizes and rainfall, as evaluated from the satellite radar.

This investigation shows that industrial effluent plumes can indeed affect cloud properties and rainfall for a significant distance downwind of the source, but shows this only for the particular cloud types and air masses present on those selected occasions. It is not possible from these studies to make any estimate of the actual effect that continuous release of the industrial plumes might have upon downwind rainfall. It is also not possible to infer the effect of an industrial aerosol on precipitation from glaciating clouds from observation of its effect on warmer clouds. Indeed it is possible that the industrial smoke might contain traces of materials such as lead iodide that are known to be effective ice nucleating agents, though not as active as silver iodide. If this were the case, then the industrial smoke might even enhance precipitation from appropriate cold clouds.

The only way in which the effect of industrial pollution on annual rainfall can be resolved is to carry out a prolonged set of observations both within the pollution trail and immediately outside it, or with some similar program design. Such an investigation, soon to be published, has been undertaken by Givati and Rosenfeld (2003) in relation to urban and industrial pollution in California. Long-term reliable rainfall records are available for many areas, and comparison pairs were chosen, one of each pair in the mountains about 50-100km downwind from the pollution source and the other on the coast in a nearby unpolluted region. The results, to be presented at a conference early in 2003, give very clear support to the view that such industrial pollution can lead to a significant reduction in rainfall from orographic clouds (the main precipitation source) in nearby downwind mountainous areas.

Even more persuasive and relevant, however, is long-term data taken downwind from the major industrial and urban pollution source presented by Los Angeles, particularly since independent studies quantify the amount of polluting smoke produced. With the introduction of strong pollution control measures in the city in the 1970s, the actual pollution source strength has declined significantly over the past 30 years, and the downwind rainfall has recovered. These results show not only a significant effect of pollution tracks on downwind precipitation, but also that these effects can be reversed by controlling the pollution at its source.

There is, however, an important caution to be noted, and this is that results found in California cannot be simply assumed to be transferable to the Australian scene. The background structure of the clouds may be different, both in droplet concentration and in cloud dynamics. The background aerosols and also the industrial aerosols may also be different from those in California, and finally the topography of the mountains and dynamics of the air currents are also both different. Nevertheless, these results are worthy of close examination in relation to the Australian situation.

Note, incidentally, that rainfall inhibition effects are not limited to urban pollution. Indeed Rosenfeld et al. (2001) have found very similar effects produced by desert dust in Israel. They conclude that this process might provide a feedback loop resulting in prolonged dry periods, a possibility that is also important in Australia. It is also possible for other aerosols, such as natural salt particles, which might not be classified as “pollution” to influence rainfall in a contrary direction, as with salt dust entrained from the Aral Sea near Israel (Rudich et al. 2000).

Conclusions

Cloud microphysics theory and field observation both confirm that added aerosol particles can affect the nucleation of cloud droplets and thus the droplet number and size in clouds. Satellite observations confirm that, in at least some types of clouds, these modifications can extend downwind for several hundred kilometres and can inhibit the formation of precipitation. Convincing satellite evidence of such effects in Australia has been produced on several occasions. The big question is whether or not the effect of this on annual, or even seasonal, rainfall is significant. The actual rainfall records do not appear to show any such effect, and indeed the annual rainfall over Victoria and the Snowy Mountains catchment appears to have increased with time, although there have been large fluctuations on an annual and even a decadal scale and, in particular, a large decline over the period 1975–89 that is mirrored in the rainfall for Australia as a whole, and so not due to local pollution.

The most appropriate conclusion therefore appears to be that, while there is convincing evidence that industrial pollution such as that originating near Adelaide can affect the droplet size and very likely the precipitation from certain types of clouds up to several hundred kilometres downstream from the source, it has not yet been established that the effect is similar for the range of clouds affecting the region or that it has any significant effect on the total annual rainfall. This applies with even greater strength to rainfall in the Snowy Mountains area, where many of the rain-bearing air masses may not even pass over pollution sources area near Adelaide or elsewhere.

IV. CLOUD SEEDING AND ITS EFFECTS

Cloud seeding has been proposed as a method to counteract the presumed effects of industrial pollution upon rainfall in Victoria and the Snowy Mountains in particular, and possibly in other areas of Southeastern Australia as well. This section will examine the proposal in more detail.

Essentially all the methods of cloud seeding now in use were developed about fifty years ago. The actual seeding procedures have been refined, however, and a very significant advance has been made in radar and satellite techniques for both operational seeding and experimental evaluation. These techniques will be discussed briefly.

Hygroscopic seeding of warm clouds

Warm stratus clouds often give widespread rainfall at moderate intensity, largely generated by a coalescence mechanism because the cloud tops do not get adequately high and cold for development of significant concentrations of ice crystals. As discussed above, average cloud droplet radius has to exceed about 14µm for significant coalescence to occur, and that is inhibited in polluted air because there are many competing small condensation nuclei. Hygroscopic seeding aims to introduce an adequate concentration of relatively large salt particles, about 1–3µm in diameter just below cloud base so that they will nucleate condensation first and restrict nucleation on other smaller particles. The resulting cloud will then have larger average droplet size at its higher levels and these droplets will be able to coalesce to produce rain. This process is seen as very similar to that by which condensation nuclei are removed from continental air masses when they travel over the oceans (Rosenfeld et al. 2002a). Indeed, Rudich et al. (2002) have observed effects in Israel that can be attributed to the "cleansing" of polluted clouds by salt-particles from the Aral Sea.

This approach has some promise of success with polluted stratiform clouds, but can also enhance precipitation from large supercooled clouds by accelerating droplet accretion by falling ice crystals and raindrops.

Rosenfeld et al. (unpublished 2002b) comment that "Although far from a proven technology, hygroscopic seeding for precipitation enhancement appears to be on solid grounds." Rosenfeld bases this view on theoretical arguments about coalescence, the results of three recent seeding experiments, and numerical cloud simulations. While economical and efficient dispersion of the necessary salt nuclei has been a problem, he believes that he has now essentially solved this and hopes to have his device available for testing soon (personal communication).

While the seeding process could be regarded as "static" (only affecting the microphysics of the cloud) there is evidence from South African experiments (E.K Bigg, personal communication) that best results are achieved in cumulus clouds when there is a quite large wind shear. The nucleated precipitation then falls outside the initial updraught column and initiates further vertical circulation, extending the area of the cloud. This is then a type of "dynamic" seeding.

A wide survey of the current situation in relation to hygroscopic seeding is given in the report of an international workshop conducted under the auspices of the WMO in 1999 (Foote and Bruintjes 2000). The workshop considered recent experiments in South Africa and Mexico, among other places, and concluded:

1. The seeding evidence [is] highly interesting, exciting, provocative, and problematical.
2. The fact that seeding results appeared late [is] not understood and [is] viewed as an important weak link in accepting the results at face value.
3. Even given the single-cloud results, one could not automatically expect that wide-area seeding would produce substantial wide-area rainfall increases.
4. The hygroscopic seeding technique has not yet been demonstrated to be cost-beneficial for a wide-area seeding program.
5. The hygroscopic seeding results cannot be automatically transferred to a new geographic area, since the background aerosol and probably other things are very important.
6. "It seems particularly important to avoid now the often reckless enthusiasm that greeted AgI seeding in the 1950s, in many cases continuing up to the present."

Dry-ice seeding

One of the earliest cloud seeding procedures used dry ice (solid CO_2) dropped into the cloud to initiate droplet freezing (which it can easily do, since its sublimation temperature is about –78°C). This techniques was fine for clearing low fog clouds in very cold environments, and worked satisfactorily when the seeding agent was dropped into the tops of cumulus clouds. It is, however, inconvenient to use and has largely been abandoned as a seeding method.

Liquid CO_2 seeding

A new method of cloud seeding has been proposed recently by Professor Norihiko Fukuta (1998) of the University of Utah. Essentially it involves releasing a trail of liquid CO_2 from a room-temperature pressure tank on an aircraft flying just above the freezing level in a cloud. The released liquid freezes immediately to dry ice as its pressure is relieved, and this in turn causes freezing of the surrounding cloud water droplets. The claimed benefits of this method of seeding are that it produces a long continuous line of seeded cloud near the freezing level. This line is warmed by the effect of freezing of water droplets, and moves upwards creating parallel twin vortices which spread out on reaching the top of the cloud and distribute the seeding effect. Another claimed benefit is that the number of ice crystals produced by the seeding remains essentially constant as the cloud vortices rise, since all the ice nucleation occurred at the level of CO_2 release, while with AgI seeding the smaller seeding particles continue to nucleate new ice crystals as the air cools. According to Wakimizu et al (2000), the method has been tested in Japan and found to work as predicted, at least in one season of experiment.

Silver iodide seeding

Seeding clouds with silver iodide (AgI) has been the preferred method of cloud modification for nearly all of the past fifty years. It has the benefit of flexibility, since the smoke containing the AgI particles can be released from aircraft, from ground generators, or even from rockets fired into clouds. There has been little change in these techniques over that time, but some current operators prefer to use flares containing AgI that are mounted on the wings of small aircraft, rather than requiring the storage tanks and other complications involved with using AgI dissolved in acetone with added sodium or ammonium iodide.

Silver iodide released into the up-draught of a cloud certainly distributes the nucleating particles throughout the cloud and leads to the formation of more ice crystals once the cloud temperature falls below about –10°C. These ice crystals grow at the expense of water droplets and become large enough to fall against the updraught, ultimately becoming raindrops if the cloud thickness is sufficient. The latent heat released by droplet freezing also increases the updraught buoyancy and makes growth of the cloud more vigorous. All these effects have been found to stimulate rainfall in suitable clouds. There are, however, contra-indications in the case where there are already adequate numbers of ice crystals in the upper parts of the cloud, for addition of more nucleating particles may then produce too great a concentration of ice crystals which fail to grow because of competition.

Since use of aircraft-mounted flares is advocated by Mr Gingis, a little further comment is warranted. One of the claimed advantages is that flares allow the operator to inject a precise amount of seeding material into a cloud. While this is true in one sense, the seeding recipe must be for the release of a certain number of flares, and fractional flare release is not possible. With liquid-burning generators, however, the burn time, and thus the amount of seeding smoke released, can be adjusted to any desired amount. The disadvantage of liquid generators is the general requirement for a larger and thus more expensive aircraft. Either type of generator could be used if the smoke is to be released from the ground, a technique that is much less flexible but much less expensive than an aircraft operation. One other problem with airborne flare seeding has, however, been identified by Rosenfeld et al (unpublished 2002b), namely that burning fragments from airborne flares have been observed to reach the ground and have in at least one instance started a grass fire.

Conclusions

There are several well established techniques for modifying the droplet structure of clouds, and most of these modifications have an effect upon the general dynamics of the cloud as well because of the latent heat released in either condensation or freezing. Most techniques have the potential to increase precipitation from a cloud with appropriate microstructure, dynamics, and native aerosol content, but most also have the potential to decrease precipitation if used on the wrong clouds or in the wrong way. If the conditions are right, then a combination of hygroscopic seeding with large salt particles and seeding with silver iodide smoke has the potential to increase precipitation from individual clouds, and probably over extended areas where cloud structure and dynamics are similar. In many cases only one of these techniques need be used.

It is not possible to say in advance whether a particular seeding method will enhance precipitation in a particular area of Australia, for example the Snowy Mountains or the plains of Western Victoria, or whether it will counteract the effect of industrial pollution, if there be one in this area. All that can be said, in the absence of experimental evidence, is that the potential exists if it is used correctly, but this says nothing about the magnitude of the results likely to be achieved. Whether this is a cost-effective way of going about relieving water problems will be discussed in another section of this report.

V. OVERSEAS EXPERIENCE WITH CLOUD-SEEDING

Overseas experience with cloud seeding experiments or operations is of only limited value because, as essentially all scientists agree, the level of success will depend critically upon local conditions of geography and wind direction, topography, cloud origin and type, and the nature of background aerosols. Nevertheless, a brief survey is illuminating.

Israel

Cloud seeding experiments have been conducted in Israel since 1961. The most recent experiments (Israeli–3) have been analysed in an unpublished paper by Rosenfeld (2002). He concludes that “seeding has differential effects, positive in the north and no-effect in the south of Israel, for all the three periods of Israeli 1, 2 and 3 independently.” He attributes the zero result in the south to the effect of desert dust.

Assessments of the success of the Israeli programs by Gagin and others, however, have excited strong criticism, particularly from the cloud physics group at the University of Washington in Seattle (Rangno and Hobbs 1995). A further paper by Rosenfeld (1997) replies to these criticisms, as does a short paper by Dennis and Orville (1997), but in a further reply Rangno and Hobbs (1997) stand by their original views. The criticisms by Rangno and Hobbs refer both to the design of the experiment and the analysis of the results, and the matter cannot be considered to be clearly resolved.

South Africa

These experiments used hygroscopic seeding techniques. Little has been published that I am aware of, but Dr Keith Bigg, formerly with CSIRO but now long retired and working as an independent consultant, spent time in Africa with the experiment and gave me the benefit of his conclusions. He reports that the seeding has positive results only in the case of thunderstorm clouds, and then only if there is considerable wind-shear to distort the ascending air columns away from the vertical. It appears that in these cases the seeding leads to modified dynamics and a horizontal expansion of the cloud, giving greater rainfall. He says that the experiment has essentially lapsed following the death of its main proponent, Graham Mather.

Texas

This experiment is the one most relevant to the Australian proposals. Mr John Forrest MP has visited Texas and has produced a comprehensive description of the project (Forrest 2002). Essentially the program uses silver iodide seeding from flares mounted on aircraft wings. The cloud situation is monitored by radar, and the aircraft is directed towards clouds regarded as suitable for seeding.

The initial analysis of the results of the program were published by Rosenfeld and Woodley (1989). Because of the way the experiment was designed, with individual cloud cells being seeded rather than whole areas, all that could be determined was the ratio of apparent (radar-derived) rainfall from seeded cells compared with that from unseeded cells. Rainfall from individual cells was assessed at half-hour intervals for a time of about three hours after seeding. The average increase produced by seeding was assessed at 20 percent, but they conclude that “because of the small sample and large natural rainfall variability, it is likely that chance has confounded this assessment of the results of treatment.” A later assessment (Rosenfeld and Woodley (1993) examined seeding results for a total of 183 cloud cells (93 seeded and 90 unseeded) and concluded that the seeded cells grew both vertically and horizontally and that radar estimates of the amount of precipitable water within the clouds indicated an increase of about 130 percent.

Further insight into the problems associated with individual cloud seeding are discussed by Rosenfeld and Woodley (1997). They point out that “In the real world there may be a hierarchy of clouds on any given day, some that will respond to seeding and others that are able to grow to massive stature without seeding intervention.” There can even be negative effects: “The consequence of seeding too late in the life cycle of a cloud is usually accelerated dissipation.” All this, in addition to detailed knowledge of the clouds on any given day and their structure, “requires great care in the placement of the nucleant either in the updraught directly near cloud top or in the strong inflow region at cloud base in well-developed systems.”

Still more recently, Woodley and Rosenfeld (2002) in an as yet unpublished paper re-examine the methods used to evaluate rainfall from treated cloud cells using radar techniques and suggest a new approach. Their analysis was made more complicated by the fact that the Texas program is “operational” rather than being a research program, so that reliable conclusions are more difficult to draw. Their analysis concluded that “apparent seeding effects as large as +75% are indicated. It is likely, however, that selection bias confounded these assessments” though they are “led to the conclusion that the indicated differential effects of seeding may be real.”

There are, however, further questions that hang over an experiment, or rather an “operation” such as that carried out in Texas. Even if the effect of seeding individual cloud cells leads to radar indications of precipitation-sized drops within these cells, how much rain actually reaches the ground? And how much extra rainfall does the seeding operation produce over the whole of Texas? Answers to these questions are difficult to come by and, to quote Woodley and Rosenfeld (2002), “seeded efficiency must be demonstrated or the projects will end ultimately in disillusionment and controversy.”

VI. AUSTRALIAN EXPERIENCE WITH CLOUD SEEDING

Cloud seeding operations commenced in the CSIRO Division of Radiophysics in 1947, making use of wartime developments in radar. The Division was subsequently divided in two and a new Division of Cloud Physics continued the work until it was amalgamated with the Melbourne-based Division of Atmospheric Research in the mid 1980s. One or other of these Divisions carried out cloud seeding experiments in Tasmania, the Blue Mountains (Sydney catchment area), the Snowy Mountains, and later in tropical Queensland. The Tasmanian experiment was the most successful of these and led to an operational seeding program by the Tasmanian Hydroelectric Authority that will be discussed later. Most of the other experiments ended in controversy about the results achieved, so there is little to be gained by discussing them in any detail. An excellent historical survey of these experiments has been given by Ryan and Sadler (1995).

In the late 1970s (King 1982, Ryan and Sadler 1995) it was decided to design a very careful experiment to be carried out in Western Victoria using all the knowledge that had been gained in these other areas. The type of cloud suitable for seeding was identified, and records indicated the frequency of occurrence of weather patterns likely to give rise to these cloud types. An economic cost-benefit analysis was also carried out for various levels of seeding success. Unfortunately during the 1979 and 1980 seasons, though the hoped-for meteorological conditions eventuated several times, the clouds were always fully glaciated so that there was nothing to be gained by seeding. Similar conditions occurred in later years, and the experiment was abandoned. Despite this, there is much to be learnt from the approach adopted in this experiment and documented in the report. In particular it draws attention (King 1982) to the necessity for a realistic cost-benefit analysis that considers the purpose for which any additional rainfall is to be used.

The Snowy Mountains Experiment

This was one of the first Australian experiments and was begun by CSIRO in the period 1955-1959. The original CSIRO analysis suggested a rainfall increase as high as 19%, but this was contested by the Snowy Mountains Hydroelectric Authority (SMHEA), and the results were finally deemed to be “marginal” and “inconclusive”, but “encouraging”.

Since that time, the attitude of the SMHEA has changed completely, and the Authority is reported as planning a further long-term seeding experiment in which it is hoped that the flow of the Murray River can be increased by something like 100 GL per year. Since the released flow of the Murray is around 1200GL per year and the natural variability in this flow is from 30% to 250% of the average, i.e. from about 400 to 3000 GL per year, it would be extremely difficult to detect this increase of about 8% in an experiment lasting only a few years. If an increase of as much as 30% could be achieved, as claimed by Mr Gingis, then its detection would be much easier.

The technique proposed is to include an indium salt (indium sesquioxide, In_2O_3) in the silver iodide smoke from ground generators during the winter season. The extent of snowfall attributable to the seeding would be estimated by analysing for the ratio of silver to indium in snow samples, with a record of snow depth and density also being kept (McGurty 1999). (The indium salt is not an effective nucleating agent, and so gives a measure of accidental incorporation in natural snow.)

Whatever is done in relation to this experiment, it seems obvious that a balanced scientific committee should be established to review the structure of the planned experiment before it is commenced and to oversee the analysis of the resulting data. Without such a provision it is almost inevitable that the experiment will be seen as failing to demonstrate anything on a scientific basis.

The Tasmanian Experiment

The most successful and long-running Australian cloud seeding program is that in Tasmania. A very recent analysis of the program has been made by Pook and Budd (2002) of the Antarctic CRC at the University of Tasmania. The experimental program was conducted under the supervision of CSIRO from 1964 to 1971 (Stage I), and then in a modified form by Hydro Tasmania between 1979 and 1983 (Stage II). As well as investigating the increase in rainfall achieved in the target area, the review also examined concerns that rainfall on the West coast of Tasmania had been increased and that on the East coast decreased by the seeding operations. There is no obvious physical basis for the first of these possibilities, but the second could clearly arise from clouds being "milked" of their water content in passing over the target area in central Tasmania. Such questions can be decided only by careful analysis of rainfall statistics for all the areas involved.

Tasmanian rainfall has declined by about 6 percent over the period 1919–1995 (Hennessy et al. 1999), though the statistical significance of that figure is not large. Pook and Budd (2002) identified a similar decrease in the Southern midlands, and a notable decline in this region over the decade 1991–2000. Such trends are of obvious concern to the hydroelectric power industry.

The conclusions of the report were that:

1. "There has been an apparent modest increase in rainfall in the Target Area for seeded cases in Stage I, and an apparent increase in rainfall for those cases in Stage II where suitable stratiform cloud was seeded in a Westerly airstream."
2. "There is no detected evidence of significant influences of seeding operations outside the target area, nor have we detected any evidence of significant influences of seeding operations on agricultural areas in Tasmania."

In this connection, the "modest increase" noted for Stage I is about 8%, though varying between seasons and being slightly negative in spring. The results for Stage II are more complex and variable. When stratified according to wind direction and other criteria, quite large increases are noted under some conditions, but the number of cases available for analysis makes any conclusions statistically unreliable. Such "post-experiment" stratification of the data is valuable in terms of the possible design of a subsequent experiment, but does not constitute a statistically reliable conclusion.

The report concludes by recommending: (a) the introduction of appropriate randomisation procedures in any subsequent operation (these were omitted when the seeding became "operational"), (b) a periodic independent review of the experimental data, (c) initiation of a project to investigate cloud climatology in the target area and a study of long-term rainfall trends in Tasmania.

Persistence effects

It is worthwhile to mention an effect that has been proposed by E.K Bowen (Bowen 1966, Bigg and Turton 1988) that could impact upon the results of all randomised experiments using silver iodide. Some early experiments appeared to show marked positive results in the first year of operation, but the apparent rainfall increase declined in subsequent years. Bigg proposed that the silver iodide somehow remained around in the target area so that nominally unseeded periods were actually seeded by the residues from the previous seeded period. Certainly such an effect would explain the observations, if they are real, and would reduce the assessed effectiveness of all randomised seeding experiments.

There are several problems with this explanation, however. The major one is that silver iodide is decomposed by sunlight (like the silver bromide in photographic film) so that it is unlikely that it can actually remain in the environment in its original form. The explanation that has been proposed is that, since certain bacteria are also known to act as reasonably efficient ice nuclei, perhaps such bacteria living on the leaves of plants are able to ingest the silver iodide and so increase their efficiency. This has not been demonstrated, however, and remains a speculation. Nevertheless, the design of seeding experiments should bear the possibility in mind.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Effect of pollution on rainfall in Australia

In the absence of adequately specific information from Mr Gingis on the basis for claims about the effects of pollution on Australian rainfall, I have assumed that they were based upon official District Annual Rainfall (DAR) data similar to that for Region 71 or the Snowy Mountains. While the initial evidence did seem convincing, the Bureau was able to show that an equally good, if not superior, explanation was possible in terms of the way in which the figures in the DAR historical record had been constructed. Informal information from the Bureau, as well as comments from Professor Rosenfeld, indicate that similar alternative explanations were brought forward for other districts that he had examined. Since there has been significant development in these mountain regions, both for hydroelectric resources and for tourism, in the past fifty years, it is not surprising that similar shifts of observing stations occurred in many places.

Nevertheless, there is convincing satellite evidence that pollution from industrial sites near Adelaide does have an effect on cloud structure downwind for several hundred kilometres, and it would not be surprising if this had some effect on actual rainfall on the ground. Similar effects have been observed from the LaTrobe Valley and also near sites of industrial pollution along the Queensland coast. The magnitude of any effect on annual rainfall, however, even in regions clearly within the presently observed plumes, remains to be established and it may not be significant.

My conclusion, therefore, is that, while industrial and urban pollution could be having an effect on cloud microstructure and perhaps rainfall downwind of and close to the source, and has had demonstrated effects in particular locations in other countries, there is no convincing evidence that this has had any significant effect on annual rainfall in Southeast Australia, and specifically in the Snowy Mountains or the Victorian Alps.

Possible effectiveness of cloud seeding

Even setting aside this negative, or at least non-positive, conclusion about the effect of industrial and urban pollution on rainfall in Australia, it should be recognised that natural aerosols such as soil dust can have an effect upon cloud structure and therefore possibly upon rainfall. The situation can be very different in different countries or in different places in the same country, so that it is not possible to transfer the conclusions from the Israel, Texas, or even Tasmanian experience to Victoria or New South Wales. These experiments can, however, provide a valuable guide, and on the whole show the possibility of an increase in rainfall of up to about 10% in favourable places. Most of these experiments, however, have been and still are enmeshed in controversy. This is partly because they have been designed, operated, and analysed by a single group rather than involving the wider meteorology/cloud-physics community, and partly because any experiment that looks promising has been pushed prematurely to the operational stage.

On the basis of overseas experience, although experiments involving the seeding of individual clouds may look convincing, it is ultimately necessary to examine actual rainfall records to evaluate the effectiveness of any cloud seeding operation. Information gained from radar or satellite observations can be very valuable, but does not tell us how much rain reaches the ground.

The seeding strategies proposed by Professor Rosenfeld are adequately flexible to cover a variety of cloud situations, and appear to be appropriate in Australia. In essence these strategies are all refinements of techniques developed long ago, but increasing knowledge and experience should have enabled them to be applied in a more effective manner. Developments in remote cloud monitoring have also been significant. While the strategy of seeding individual clouds has the advantage that seeding techniques can be adapted to the particular cloud being treated, this carries the disadvantage of requiring remote monitoring of all clouds and remote direction of aircraft, both of which reduce greatly the available effective seeding time and thus increase the cost of the operation.

Despite these advances, it is likely that experiments could yield either no discernible result, a positive result implying a rainfall increase of order 10%, or even a negative result of similar magnitude. It is therefore necessary for a carefully designed seeding and evaluation program to be carried out if any reliable conclusions are to be reached. In view of the variability of natural rainfall, particularly in Australia, such a program would need to be carried out over at least as long as five years to achieve a reliable result. Because the cost of an experimental program is very significant, and the cost of an operational program even more so, it is important that a cost-benefit analysis be carried out in advance for the particular program contemplated.

My conclusion is that, while it is by no means established that a cloud seeding program could increase the rainfall in Victoria, or specifically in the Snowy Mountains and Victorian Alps regions, whether there are effects of urban and industrial pollution or not, there is a possibility of an increase of around 10%. Experience with past CSIRO seeding programs in the Snowy Mountains and Western Victoria does not hold out much promise of reaching a generally agreed conclusion, but new and more efficient methods of seeding coupled with radar and satellite observations might improve prospects. Experience from programs in other countries is controversial in the matter of their success in achieving an increase in rainfall, and in any case their experience is not directly transferable to the Australian situation. While indirect radar and satellite techniques should certainly be employed in any such program, its final effectiveness must be judged in terms of rainfall actually reaching the ground over a defined broad area.

An alternative approach?

The atmospheric situation in Australia differs greatly from that in the Northern hemisphere in that pollution is very mild, and the sources identified by Professor Rosenfeld are isolated and well defined operations such as power stations and smelters. It would therefore seem to be an obvious solution to try to reduce or offset the effects at the source rather than hundreds of kilometres away. If this could be done, assuming the sources are in fact causing as rainfall decrease, then all intervening areas would also benefit.

It is not clear whether there has been any detailed study of the pollution plumes produced by these sources. Doubtless environmental legislation was invoked during their construction to place reasonable limits on total solids released in the plumes, but what is really required is a microscale analysis of the particulate matter. It may then be possible to identify the nucleating particles responsible for producing numerous small cloud droplets and to enhance their removal from the smoke, for example by further stages of electrostatic precipitation. Since these operations are conducted by major industries or semi-government entities, and since their number is not large, such a clean-up operation should, if it is possible, not be difficult to implement. It would have the huge advantage of involving a “once-only” expenditure instead of the unending expense of a cloud-seeding operation.

Since seeding some clouds with large condensation nuclei is known to be effective both naturally (e.g. from the Aral Sea in Israel) and artificially, another possibility that might be investigated is to seed the smoke plumes from the offending sources with large numbers of appropriately sized (1–2 μm) salt particles. Since the plumes are initially hot and confined in chimneys, this might be achieved using a specially designed spray of salty water injected into the hot chimney flow after the electrostatic precipitation stage. Since most of the operations are close to the sea, simple sea-water might be an appropriate salt source. Quite large quantities would be required, which makes this source attractive. Again, if such a solution were effective it would be very much less expensive that an airborne cloud-seeding operation. I have not given more than preliminary consideration to this idea.

Note that the value of attempting to implement either of these approaches depends upon the validity of the contention that this industrial pollution is actually significantly reducing overall downwind rainfall in Australia, and this has not in my view been conclusively established. Since cloud traces observed by satellite AVHRR can be taken as a reliable indicator of cloud-top droplet size (which is not the same as an indicator of rainfall), and satellite radar measurements show up precipitation-sized drops, then experiments with either of these approaches could be undertaken at some suitably isolated but large-scale pollution source of the relevant type and monitored by satellite imaging. Further prolonged experimentation using observations of actual precipitation at ground level would, however, be required to establish whether or not the technique is appropriate for increasing accumulated rainfall in that place.

An experimental program?

If any cloud seeding program is contemplated, then

1. It should be designed and supervised by a scientific committee with appropriate representation from both the Bureau of Meteorology and CSIRO, as well as independent scientific members.
2. The Committee may decide to contract out the actual operation of the program, but should maintain control and supervision of the procedures adopted and of the collection and analysis of rainfall data.
3. A cost-benefit analysis should be carried out before any such program is established.
4. The target area for any such program should be left for decision by the scientific committee, bearing in mind the estimated likelihood of success and the potential cost-benefit ratio.
5. The criterion for success of the program should be the extent to which it increases annual rainfall over the target area, measured at ground level.

It is not the role of this report to comment on how such a program might be funded. The fact that CSIRO does not have any experimental cloud seeding program in operation at present, however, suggests that their assessment of priorities within the available budget places other activities ahead of the debatable benefits and uncertainty of success in any such program. The program is likely to involve substantial outlays for monitoring equipment, aircraft modification, etc and substantial operational costs and will need to be continued for at least five years, and possibly longer, to achieve reliable results.

If the alternative approach of reducing pollution at its source, or of seeding the source plume with large hygroscopic nuclei is to be evaluated, then very similar design and assessment arrangements should be put in place.

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Dr William Woodley, President, Woodley Weather Consultants, Littleton, Colorado, USA.

Other people consulted:

Mr Roger Beale, Secretary, Dept. of the Environment and Heritage

Mr Terry Charlton, CEO, Snowy Mountains Hydro Authority (SMHEA)

Mr Barry Dunn, SMHEA

Mr Michael Fitzgerald, Advisor to the Federal Minister for the Environment and Heritage

Mr John Forrest, MP, Federal Member for Mallee.