

ANNEX III

Annex to agenda item 5.6 of the general summary

WMO STATEMENT ON THE STATUS OF WEATHER MODIFICATION

INTRODUCTION

For thousands of years people have sought to modify weather and climate so as to augment water resources and mitigate severe weather. The modern technology of weather modification was launched by the discovery in the late 1940s that supercooled cloud droplets could be converted to ice crystals by insertion of a cooling agent such as dry ice or an artificial ice nucleus such as silver iodide. Over 50 years of subsequent research have greatly enhanced our knowledge about the microphysics, dynamics and precipitation processes of natural clouds (rain, hail, snow) and the impacts of human interventions on those processes.

Currently, there are dozens of nations operating more than 100 weather modification projects, particularly in arid and semi-arid regions all over the world, where the lack of sufficient water resources limits their ability to meet food, fibre, and energy demands. The purpose of this document is to present a review of the status of weather modification.

The energy involved in weather systems is so large that it is impossible to create artificially rainstorms or to alter wind patterns to bring water vapour into a region. The most realistic approach to modifying weather is to take advantage of microphysical sensitivities wherein a relatively small human-induced disturbance in the system can substantially alter the natural evolution of atmospheric processes.

The ability to influence cloud microstructures has been demonstrated in the laboratory, simulated in numerical models, and verified through physical measurements in some natural systems such as fogs, layer clouds and cumulus clouds. However, direct physical evidence that precipitation, hail, lightning, or winds can be significantly modified by artificial means is limited. The complexity and variability of clouds result in great difficulties in understanding and detecting the effects of attempts to modify them artificially. As knowledge of cloud physics and statistics and their application to weather modification has increased, new assessment criteria have evolved for evaluating cloud-seeding experiments. The development of new equipment — such as aircraft platforms with microphysical and

air-motion measuring systems, radar (including Doppler and polarization capability), satellites, microwave radiometers, wind profilers, automated rain gauge networks, mesoscale network stations — has introduced a new dimension. Equally important are the advances in computer systems that permit large quantities of data to be processed. New datasets, used in conjunction with increasingly sophisticated numerical cloud models, help in testing various weather modification hypotheses. Chemical and chaff tracer studies help to identify air-flow in and out of clouds and the source of ice or hygroscopic nucleation as the seeding agent. With some of these new facilities, a better climatology of clouds and precipitation can be prepared to test seeding hypotheses prior to the commencement of weather modification projects.

If one were able to predict precisely the precipitation from a cloud system, it would be a simple matter to detect the effect of artificial cloud seeding on that system. The expected effects of seeding, however, are almost always within the range of natural variability (low signal-to-noise ratio) and our ability to predict the natural behaviour is still limited.

Comparison of precipitation observed during seeded periods with that during historical periods presents problems because of climatic and other changes from one period to another, and therefore is not a reliable technique. This situation has been made even more difficult with the mounting evidence that climate change may lead to changes in global precipitation amounts as well as to spatial redistribution of precipitation.

In currently accepted evaluation practice, randomization methods (target/control, crossover or single area) are considered most reliable for detecting cloud-seeding effects. Such randomized tests require a number of cases readily calculated on the basis of the natural variability of the precipitation and the magnitude of the expected effect. In the case of very low signal-to-noise ratios, experiment durations in the range of five to over 10 years may be required. Whenever a statistical evaluation is required to establish that a significant change resulted from a given seeding activity, it must be accompanied by a physical evaluation to:

- (a) Confirm that the statistically-observed change is likely due to the seeding; and
- (b) Determine the capabilities of the seeding method to produce the desired effects under various conditions.

The effect of natural precipitation variability on the required length of an experiment can be reduced through the employment of physical predictors, which are effective in direct proportion to our understanding of the phenomenon. The search for physical predictors, therefore, holds a high priority in weather modification research. Physical predictors may consist of meteorological parameters (such as stability, wind directions, pressure gradients) or cloud quantities (such as liquid water content, updraught speeds, concentrations of large drops, ice-crystal concentration or radar reflectivity).

Objective measurement techniques of precipitation quantities are to be preferred for testing weather modification methods. These include both direct ground measurements (e.g. raingauges and hail pads) and remote sensing techniques (e.g. radar, satellite). Secondary sources, such as insurance data (as have in the past been employed to show changes in hail intensity) are, at least by themselves, not held to be satisfactory in most situations.

Operational programmes should be conducted with recognition of the risks inherent in a technology which is not totally developed. For example, it should not be ignored that, under certain conditions, seeding may cause more hail or reduce precipitation. However, properly designed and conducted operational projects seek to detect and minimize such adverse effects. Therefore, weather modification managers are encouraged to add scientifically-accepted evaluation methodologies to be undertaken by experts independent of the operators.

Brief summaries of the current status of weather modification are given in the following sections. These summaries were restricted to weather modification activities that appear to be based on acceptable physical principles and which have been tested in the field.

FOG DISPERSAL

Different techniques are being used to disperse warm (i.e. at temperatures greater than 0°C) and cold fogs. The relative occurrence of warm and cold fogs is geographically and seasonally dependent.

The thermal technique, which employs intense heat sources (such as jet engines) to warm the air directly and evaporate the fog, has been shown to be effective for short periods for dispersal of some types of warm fogs. These systems are expensive to install and to use. Another technique that has been used is to promote entrainment of dry air into the fog by the use of hovering helicopters or ground-based engines. These techniques are also expensive for routine use.

To clear warm fogs, seeding with hygroscopic materials has also been attempted. An increase in visibility is sometimes observed in such experiments, but the manner and location of the seeding and the size distribution of seeding material are critical and difficult to specify. In practice, the technique is seldom as effective as models

suggest. Only hygroscopic agents should be used that pose no environmental and health problems.

Cold (supercooled) fog can be dissipated by growth and sedimentation of ice crystals. This may be induced with high reliability by seeding the fog with artificial ice nuclei from ground-based or airborne systems. This technique is in operational use at several airports and highways where there is a relatively high incidence of supercooled fog. Suitable techniques are dependent upon wind, temperature and other factors. Dry ice has commonly been used in airborne systems. Other systems employ rapid expansion of compressed gas to cool the air enough to form ice crystals. For example, at a few airports and highway locations, liquid nitrogen or carbon dioxide is being used in ground-based systems. A new technique, which has been demonstrated in limited trials, makes use of dry ice blasting to create ice crystals and promote rapid mixing within the fog. Because the effects of this type of seeding are easily measured and the results are highly predictable, randomized statistical verification generally has been considered unnecessary.

PRECIPITATION (RAIN AND SNOW) ENHANCEMENT

This section deals with those precipitation enhancement techniques that have a scientific basis and that have been the subject of research. Other non-scientific and unproven techniques that are presented from time to time should be treated with the required suspicion and caution.

Orographic mixed-phase cloud systems

In our present state of knowledge, it is considered that the glaciogenic seeding of clouds formed by air flowing over mountains offers the best prospects for increasing precipitation in an economically-viable manner. These types of clouds attracted great interest in their modification because of their potential in terms of water management, i.e. the possibility of storing water in reservoirs or in the snowpack at higher elevations. There is statistical evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of surface precipitation records from some long-term projects indicate that seasonal increases have been realized.

Physical studies using new observational tools and supported by numerical modelling indicate that supercooled liquid water exists in amounts sufficient to produce the observed precipitation increases and could be tapped if proper seeding technologies were applied. The processes culminating in increased precipitation have also been directly observed during seeding experiments conducted over limited spatial and temporal domains. While such observations further support the results of statistical analyses, they have, to date, been of limited scope. The cause and effect relationships have not been fully documented, and thus the economic impact of the increases cannot be assessed.

This does not imply that the problem of precipitation enhancement in such situations is solved. Much work remains to be done to strengthen the results and

produce stronger statistical and physical evidence that the increases occurred over the target area and over a prolonged period of time, as well as to search for the existence of any extra-area effects. Existing methods should be improved in the identification of seeding opportunities and the times and situations in which it is not advisable to seed, thus optimizing the technique and quantifying the result.

Also, it should be recognized that the successful conduct of an experiment or operation is a difficult task that requires qualified scientists and operational personnel. It is difficult and expensive to fly aircraft safely in supercooled regions of clouds. It is also difficult to target the seeding agent from ground generators or from broad-scale seeding by aircraft upwind of an orographic cloud system.

Stratiform clouds

The seeding of cold stratiform clouds began the modern era of weather modification. Shallow stratiform clouds can be under certain conditions made to precipitate, often resulting in clearing skies in the region of seeding. Deep stratiform cloud systems (but still with cloud tops warmer than -20°C) associated with cyclones and fronts produce significant amounts of precipitation. A number of field experiments and numerical simulations have shown the presence of supercooled water in some regions of these clouds and there is some evidence that precipitation can be increased.

Cumuliform clouds

In many regions of the world, cumuliform clouds are the main precipitation producers. These clouds (from small fair weather cumulus to giant thunderclouds) are characterized by strong vertical velocities with high condensation rates. They can hold the largest condensed water contents of all cloud types and can yield the highest precipitation rates. Seeding experiments continue to suggest that precipitation from single cell and multicell convective clouds have produced variable results. The response variability is not fully understood.

Precipitation enhancement techniques by glaciogenic seeding are utilized to affect ice phase processes while hygroscopic seeding techniques are used to affect warm rain processes. Methods to assess these techniques vary from direct measurements with surface precipitation gauges to indirect radar-derived precipitation estimates. Both methods have inherent advantages and disadvantages.

During the last 10 years there has been a thorough scrutiny of past experiments using glaciogenic seeding. The responses to seeding seem to vary depending on changes in natural cloud characteristics and in some experiments they appear to be inconsistent with the original seeding hypothesis.

Experiments involving heavy glaciogenic seeding of warm-based convective clouds (bases about $+10^{\circ}\text{C}$ or warmer) have produced mixed results. They were intended to stimulate updraughts through added latent heat release which, in turn, was postulated to lead to an

increase in precipitation. Some experiments have suggested a positive effect on individual convective cells but conclusive evidence that such seeding can increase rainfall from multicell convective storms has yet to be established. Many steps in the postulated physical chain of events have not been sufficiently documented with observations or simulated in numerical modelling experiments.

In recent years, the seeding of warm and cold convective clouds with hygroscopic chemicals to augment rainfall by enhancing warm rain processes (condensation/collision-coalescence/break-up mechanisms) has received renewed attention through model simulations and field experiments. Two methods of enhancing the warm rain process have been investigated: first, seeding with small particles (artificial CCN with mean sizes about 0.5 to 1.0 micrometres in diameter) is used to accelerate precipitation initiation by stimulating the condensation-coalescence process by favourably modifying the initial droplet spectrum at cloud base; and second, seeding with larger hygroscopic particles (artificial precipitation embryos about 30 micrometres in diameter) to accelerate precipitation development by stimulating the collision-coalescence processes. A recent experiment utilizing the latter technique indicated statistical evidence of radar estimated precipitation increases. However, the increases were not as contemplated in the conceptual model but seem to occur at later times (one to four hours after seeding), the cause of this effect is not known.

Recent randomized seeding experiments with flares that produce small hygroscopic particles in the updraught regions of continental, mixed-phase convective clouds have provided statistical evidence of increases in radar-estimated rainfall. The experiments were conducted in different parts of the world and the important aspect of the results was the replication of the statistical results in a different geographical region. In addition, physical measurements were obtained suggesting that the seeding produced a broader droplet spectrum near cloud base that enhances the formation of large drops early in the lifetime of the cloud. These measurements were supported by numerical modelling studies.

Although the results are encouraging and intriguing, the reasons for the duration of the observed effects obtained with the hygroscopic particle seeding are not understood and some fundamental questions remain. Measurements of the key steps in the chain of physical events associated with hygroscopic particle seeding are needed to confirm the seeding conceptual models and the range of effectiveness of these techniques in increasing precipitation from warm and mixed-phase convective clouds.

Despite the statistical evidence of radar estimated precipitation changes in individual cloud systems in both glaciogenic and hygroscopic techniques, there is no evidence that such seeding can increase rainfall over significant areas economically. There is no evidence of any extra-area effects.

HAIL SUPPRESSION

Hail causes substantial economic loss to crops and property. Many hypotheses have been proposed to suppress hail and operational seeding activities have been undertaken in many countries. Physical hypotheses include the concepts of beneficial competition (creating many additional hail embryos that effectively compete for the supercooled water), trajectory lowering (intended to reduce the size of hailstones) and premature rainout. Following these concepts, seeding methods concentrate on the peripheral regions of large storm systems, rather than on the main updraught.

Our understanding of storms is not yet sufficient to allow confident prediction of the effects of seeding on hail. The possibilities of increasing or decreasing hail and rain in some circumstances have been discussed in the scientific literature. Supercell storms have been recognized as a particular problem. Numerical cloud model simulations have provided insights into the complexity of the hail process, but the simulations are not yet accurate enough to provide final answers. Scientists in operational and research programmes are working to delineate favourable times, locations and seeding amounts for effective modification treatments.

A few randomized trials have been conducted for hail suppression using such measures as hail mass, kinetic energy, hailstone number and area of hailfall. However, most attempts at evaluation have involved non-randomized operational programmes. In the latter, historical trends in crop hail damage have often been used, sometimes with target and upwind control areas, but such methods can be unreliable. Large reductions have been claimed by many groups. The weight of scientific evidence to date is inconclusive, neither affirming nor denying the efficacy of hail suppression activities. This situation is motivation for operational programmes to strengthen the physical and evaluation components of their efforts.

In recent years, anti-hail activities using cannons to produce loud noises have re-emerged. There is neither a scientific basis nor a credible hypothesis to support such activities.

Significant advances in technology during the last decade have opened new avenues to document and better understand the evolution of severe thunderstorms and hail. New experiments on storm organization and the evolution of precipitation including hail are needed.

OTHER SEVERE WEATHER MODERATION

Tropical cyclones contribute significantly to the annual rainfall of many areas, but they are also responsible for considerable damage to property and for a large loss of life. Therefore, the aims of any modification procedure should be to reduce the wind, storm surge and rain damage, but not necessarily the total rainfall. Hurricane modification experiments were conducted in the 1960s and early 1970s. However, there is no generally accepted conceptual model suggesting that hurricanes can be modified.

While modification of tornadoes or of damaging winds is desirable for safety and economical reasons, there is presently no accepted physical hypothesis to accomplish such a goal.

There has been some interest in the suppression of lightning. Motivation includes reducing occurrences of forest fires ignited by lightning and diminishing this hazard during the launching of space vehicles. The concept usually proposed involves reducing the electric fields within thunderstorms so that they do not become strong enough for lightning discharges to occur. To do this, chaff (metallized plastic fibres) or silver iodide have been introduced into thunderstorms. The chaff is postulated to provide points for corona discharge which reduces the electric field to values below those required for lightning, whereas augmenting the ice-crystal concentration is postulated to change the rate of charge build up and the charge distribution within the clouds. Field experiments have used these concepts and limited numerical modelling results have supported them. The results have no statistical significance.

INADVERTENT WEATHER MODIFICATION

There is ample evidence that biomass burning, and agricultural and industrial activities modify local and sometimes regional weather conditions. Land-use changes (e.g. urbanization and deforestation) also modify local and regional weather. Air quality, visibility, surface and low-level wind, humidity and temperature, and cloud and precipitation processes are all affected by large urban areas. As environmental monitoring and atmospheric modelling capabilities are improved, it is increasingly evident that human activities have significant impacts on meteorological parameters and climatological mechanisms that influence our health, productivity and societal infrastructure. Inadvertent effects need to be considered in the design and analyses of weather modification experiments and operations (e.g. changes in background aerosol distributions affect the cloud structure and may affect precipitation processes).

ECONOMIC, SOCIAL AND ENVIRONMENTAL ASPECTS OF WEATHER MODIFICATION

Weather modification is sometimes considered by countries when there is a need to improve the economy in a particular branch of activity (for example, increase in water supply for agriculture or power generation) or to reduce the risks that may be associated with dangerous events (frosts, fogs, hail, lightning, thunderstorms, etc.). Besides the present uncertainties associated with the capability to reach such goals, it is necessary to consider the impacts on other activities or population groups. Economic, social, ecological and legal aspects should be taken into account. Thus, it is important to consider all the important complexity and recognize the variety of possible impacts, during the design stage of an operation.

Legal aspects may be particularly important when weather modification activities are performed in the

proximity of borders between different countries. However, any legal system aimed at promoting or regulating weather modification must recognize that scientific knowledge is still incomplete.

The implications of any projected long-term weather modification operation on ecosystems need to be assessed. Such studies could reveal changes that need to be taken into account. During the operational period, monitoring of possible environmental effects should be undertaken as a check against anticipated impacts.

SUMMARY STATEMENT AND RECOMMENDATIONS

To answer the need for more water and less hail in many regions of the world, some progress has been made during the past 10 years in the science and technology of weather modification. Large numbers of programmes in fog dispersion, rain, snow enhancement and hail suppression are in operation. Several research experimental programmes are supported in some countries and include randomized statistical evaluations. Improved observational facilities, computer capabilities, numerical models and understanding now permit more detailed examination of clouds and precipitation processes than ever before, and significant advances are consequently possible. New technologies and methods are starting to be applied and will help to lead to further understanding and development in this field.

In the light of this review of the status of weather modification, the following recommendations are made to interested Members of WMO:

- (a) Cloud, fog and precipitation climatologies should be established in all countries as vital information for weather modification and water resource studies and operations;
- (b) Operational cloud-seeding projects should be strengthened by allowing an independent evaluation of the results of seeding. This should include measurements of physical response variables and a randomized statistical component;
- (c) Education and training in cloud physics, cloud chemistry, and other associated sciences should be an essential component of weather modification projects. Where the necessary capacity does not exist, advantage should be taken of facilities of other Members;
- (d) It is essential that basic measurements to support and evaluate the seeding material and seeding hypothesis proposed for any weather modification experiments be conducted before and during the project;
- (e) Weather modification programmes are encouraged to utilize new observational tools and numerical modelling capabilities in the design, guidance and evaluations of field projects. While some Members may not have access or resources to implement these technologies, collaboration between Member States (e.g. multinational field programmes, independent expert evaluations, education, etc.) are encouraged that could provide the necessary resources for implementing these technologies.

ANNEX IV

Annex to agenda item 5.6 of the general summary

GUIDELINES FOR ADVICE AND ASSISTANCE RELATED TO THE PLANNING OF WEATHER MODIFICATION ACTIVITIES

1. These guidelines are addressed to Members requesting advice or assistance on weather modification activities. They include recommendations that are based on present knowledge gained through the results of worldwide theoretical studies as well as laboratory and field experiments. A synthesis of the main basic concepts and main results obtained in the weather modification programmes is given in the WMO Statement on the Status of Weather Modification. This Statement was revised during the twentieth session of the Executive Council Panel of Experts/CAS Working Group on Physics and Chemistry of Clouds and Weather Modification Research and was approved by the fifty-third session of the Executive Council in June 2001.

2. Members wishing to develop activities in the field of weather modification should be aware that research and operational applications are still under development. It should not be ignored that under certain conditions, seeding may be ineffective or may even enhance an undesirable effect (increase of hail, reduc-

tion in rain). However, properly designed and conducted projects seek to detect and minimize such adverse effects. It is recognized that scientific evaluation may be a difficult task, but this is the only way presently known to avoid negative results, quantify positive economic effects and allow improvements in the understanding and methodology that is used. The revised WMO Statement on the Status of Weather Modification referred to in paragraph 1 distinguishes the various types of weather modification and the degree of confidence necessary to obtain the desired effect from cloud seeding. The confidence level is very high for operational dissipation of supercooled fog and moderate for increasing snowfall from orographic clouds. The confidence level is not high for suppressing hail.

3. WMO recommends that operational cloud seeding projects for precipitation modification be designed to allow evaluation of the results of seeding through physical measurements and statistical controls associated with some randomization of the seeding events. The

physical measurements should include characterization of the seeding material. Care should be taken to engage qualified operators. The objective evaluation should be performed by a group independent of the operational one. Such programmes should be planned on a long-duration basis because precipitation variability is generally much greater than the increases or decreases claimed for artificial weather modification. The use of appropriate numerical models may help in reducing the time required to evaluate the project.

4. WMO recommends that a detailed examination of the suitability of the site for cloud seeding should be conducted similar to that done in the Precipitation Enhancement Project, for which WMO reports are available. To increase the chances of success in a specific situation, it should be verified through preliminary studies that:

- (a) The climatology of clouds and precipitation at the site indicates the possibility of favourable conditions for weather modification;
- (b) Conditions are suitable for the available modification techniques;
- (c) Modelling studies support the proposed weather modification hypothesis;
- (d) For the frequency with which suitable conditions occur, the changes resulting from the modification technique can be detected at an acceptable level of statistical significance;
- (e) An operational activity can be carried out at a cost acceptably lower than the socio-economic benefit that is likely to result.

All prospective studies require expert judgement and the results are expected to depend on the site chosen and on the season.

5. There are no quantitative criteria for the acceptance of the results of a weather modification experiment.

Acceptance will depend on the degree of the scientific objectivity and the consistency with which the experiment was carried out and the degree to which this is demonstrated. Also important are the physical plausibility of the experiment, the degree to which bias is excluded from the conduct and analysis of the experiment, and the degree of statistical significance achieved. There have been few weather modification experiments that have met the requirements of the scientific community with respect to these general criteria. However, there are exciting possibilities now for making progress in our understanding of weather modification issues using modern research tools, including advanced radar, new aircraft instruments and powerful numerical models.

6. Weather modification should be viewed as a part of an integrated water resources management strategy. Instant drought relief is difficult to achieve. In particular, if there are no clouds, precipitation cannot be artificially stimulated. It is likely that the opportunities for precipitation enhancement will be greater during periods of normal or above normal rainfall than during dry periods.

7. The Members should be aware that the scope of efforts involved in the design, conduct or evaluation of a weather modification programme precludes the WMO Secretariat from giving detailed advice. However, if requested, the Secretary-General may assist (by obtaining advice from scientists on other weather modification projects or with special expertise) on the understanding that:

- (a) Costs will be met by the requesting country;
- (b) The Organization can take no responsibility for the consequences of the advice given by any invited scientist or expert;
- (c) The Organization accepts no legal responsibility in any dispute that may arise.