WORLD METEOROLOGICAL ORGANIZATION

WMO DOCUMENTS ON WEATHER MODIFICATION
Updated in the meeting of the Expert Team on Weather Modification Research
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EXECUTIVE SUMMARY OF THE WMO STATEMENT ON WEATHER MODIFICATION

1. INTRODUCTION

1.1 The activities of the WMO in the area of weather modification are aimed at encouraging research projects, and at providing guidance about best practices for operational projects.

1.2 It should be realised that the energy involved in weather systems is so large that it is impossible to create cloud systems that rain, alter wind patterns to bring water vapour into a region, or completely eliminate severe weather phenomena. Weather Modification technologies that claim to achieve such large scale or dramatic effects do not have a sound scientific basis (e.g. hail canons, ionization methods) and should be treated with suspicion.

1.3 Purposeful augmentation of precipitation, reduction of hail damage, dispersion of fog and other types of cloud and storm modifications by cloud seeding are developing technologies which are still striving to achieve a sound scientific foundation.

1.4 Operational programmes in fog dispersion, rain and snow enhancement and hail suppression are taking place in many countries around the world. The primary aim of these projects is to obtain more water, reduce hail damage, eliminate fog, or other similar practical result in response to a recognized need. Accomplishment of the stated goals is often difficult to establish with sufficient confidence. Economic analyses show that rainfall enhancement and hail suppression operations, if successful, could have significant economic benefit, but uncertainties make investments in such efforts subject to considerable risks.

1.5 Continuing strategic research is required to investigate and explain the scientific hypotheses on which weather modification are based. Because this research is inherently focused on important atmospheric processes, it is relevant not only to weather modification but also to the improvement of weather and climate prediction that supports a wide range of applications such as water management and climate change adaptation. With sound scientific understanding of the relevant atmospheric processes, a weather modification experiment can be designed and implemented in order to test the feasibility of the activity and the validity of the underpinning scientific hypothesis and to provide the basis for operational activities

1.6 Improvements in observational facilities providing measurements of key variables and numerical modelling capabilities now permit more detailed examination of the cloud and precipitation processes and offer new opportunities for advancing the science and practice of weather modification.

1.7 Proper evaluation of a weather modification activity has several requirements. First, it needs to include a randomization process in the experimental design such that only some of the events suitable for seeding are in fact seeded. This requires objective criteria defining the start of an event so that bias is not introduced by subjective selection of seeded and unseeded events. Second, in a "primary analysis" the impact of seeding is assessed through various objective statistical techniques that compare unseeded events to seeded events and provide an estimate of the precipitation increase along with the confidence intervals in which the true impact lies. Finally, the primary analysis must be supported by a range of physically-based "secondary analyses" aimed at ensuring that the seeding hypothesis is validated .

1.8 Published studies have shown no significant impact of silver iodide (AgI) used in past weather modification operations either on human health or on the environment. However, any plans to use either a massive quantity of such a product or a different seeding agent should be accompanied with a preliminary evaluation of its potential effects on environment or on human health.

1.9 Unintended consequences of cloud seeding, such as downwind effects and environmental and ecological impacts, have not been demonstrated but cannot be ruled out.

1.10 There are mounting claims that human activities affect local and sometimes regional cloud properties and precipitation. Clarification of the existence and processes of such inadvertent weather modification and the processes involved may provide important insights into the possibilities and limitations of deliberate weather modification. In most cases of inadvertent weather modification as opposed to cloud seeding experiments, it is difficult, if not impossible, to determine and differentiate the type of particles that participate in cloud processes unless long-term measurements are available. Cloud seeding could also be used to study the effects of aerosols on clouds by seeding clouds with known particle concentrations and types as has recently been shown in the literature.

1.11 The status of different technologies applied to different weather phenomena and the physical concepts underlying them are summarized below.

2. FOG

2.1 In principle, all types of fog can be dispersed by sufficient heating or mechanical mixing, though such methods are often impractical and expensive.

2.2 Dispersal of supercooled fogs using glaciogenic materials or coolants is well established as a reliable technique feasible in certain meteorological conditions.

3. PRECIPITATION

3.1 There is considerable evidence that cloud microstructure can be modified by seeding with glaciogenic or hygroscopic materials under appropriate conditions. The criteria for those conditions vary widely with cloud type. Evidence for significant and beneficial changes in precipitation on the ground as a result of seeding is controversial and in many cases cannot be established with confidence.

3.2 Cloud seeding has been used on both cold clouds, in which glaciogenic seeding aims to induce ice-phase precipitation, and warm clouds, where hygroscopic seeding aims to promote coalescence of water droplets. There is statistical evidence, supported by some observations, of precipitation enhancement from glaciogenic seeding of orographic supercooled liquid and mixed-phase clouds and of some clouds associated with frontal systems that contain supercooled liquid water.

3.3 The use of glaciogenic agents such as silver iodide to seed supercooled cumulus clouds has produced few results of general validity. Observed responses of clouds vary widely. There are competing explanations and the questions are not yet resolved.

3.4 Seeding of convective clouds with hygroscopic materials has been shown to be adaptable to different cloud types and has produced encouraging statistical results supported by some physical observations and numerical modelling studies but is not yet an established technology.

4. HAIL

4.1 Extensively practiced glaciogenic seeding technologies have been used operationally in many parts of the world to reduce hail damage. Scientific evidence to date is inconclusive and evaluation of the results has proved difficult and the effectiveness remains controversial.

4.2 Supercell storms have been recognized as a particular problem.

4.3 Attempts to seed hailstorms with hygroscopic nuclei have been made but have not given demonstrable results.

5. TROPICAL CYCLONES (TYPHOONS AND HURRICANES)

5.1 There is no generally accepted evidence suggesting that hurricanes can be modified.

6. OTHER PHENOMENA

6.1 There are no demonstrated methods to modify tornadoes and lightning strike danger by cloud seeding.

7. GENERAL COMMENTS

7.1 The scientific status of weather modification**,** while steadily improving, still reflects limitations in the detailed understanding of cloud microphysics and precipitation formation, as well as inadequacies in accurate precipitation measurement. Governments and scientific institutions are urged to substantially increase their efforts in basic physics and chemistry research related to weather modification and related programmes in weather modification. Further testing and evaluation of physical concepts and seeding strategies are critically important. The acceptance of weather modification can only be improved by increasing the numbers of well executed experiments and building the base of positive scientific results.

7.2 Governments and other agencies involved in weather modification activities should invest in relevant education and training.

7.3 It is recognized that most weather modification projects are motivated by well documented requirements, but they also have associated risks and the results may remain uncertain. Any new project should seek advice from experts regarding the benefits to be expected, the risks involved, the optimum techniques to be used, and the likely impacts. The advisors should be as detached as possible from the project, so their opinions can be viewed as being unbiased. Operational weather modification projects should be reviewed periodically (annually if possible) to assess whether the best practices are being followed.

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WMO STATEMENT ON WEATHER MODIFICATION

1. INTRODUCTION

1.1 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 many decades research has 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. Nonetheless, to bring about deliberate and effective changes via cloud seeding has been continuously a scientific and operational challenge rather than a settled practice.

1.2 Weather modification involves three types of activities. Continuing strategic research is required to investigate and test the scientific hypotheses on which the weather modification is based. Because this research is inherently focused on important atmospheric processes, it is relevant not only to weather modification but also to the improvement of weather and climate prediction that supports a wide range of applications such as water management and climate change adaptation. With sound scientific understanding of the relevant atmospheric processes, a weather modification experiment can be designed and implemented in order to demonstrate the feasibility of the activity and the validity of the underpinning scientific hypothesis. Having completed a successful experiment, it is appropriate to undertake operational weather modification, in which the focus is on practical outcomes while maintaining practices that allow continuing scientific evaluation of the results of the operations.

1.3 Since the 1980's there has been a decline in support for weather modification research, and a tendency to move directly into operational projects. It is crucial to recognize that weather modification is still an emerging technology. Uncertainties inherent in the current technologies can only be addressed by programmes of focused research that lead to deeper understanding of the effects of cloud seeding on cloud and precipitation development. Increasing the scientific understanding will also benefit several other branches of meteorology and climate change studies.

1.4 Currently, there are dozens of nations operating hundreds of 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 an overview of the status of weather modification.

1.5 It should be realised that the energy involved in weather systems is so large that it is impossible to create cloud systems that rain, alter wind patterns to bring water vapour into a region, or completely eliminate severe weather phenomena. The only credible 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.

1.6 Cloud structure can vary widely from region to region. Seeding results in one geographic area cannot be automatically assumed to apply to another area. Transferability should be carefully considered, since, in addition to meteorological factors, differences in aerosol and trace gas constituents, surface characteristics and other factors may also cause unexpected variations in cloud behaviour and cloud response to intervention.

1.7 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.

1.8 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, chemistry 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 raingauge networks, mesoscale observing networks have introduced a new dimension. Equally important are the advances in computer systems and new algorithms that permit large quantities of data to be processed and models with more detailed description of cloud processes to be run in relatively short time.

1.9 The new datasets used in conjunction with increasingly sophisticated numerical models help in testing the weather modification hypotheses. However, careful measurement of key variables, such as precipitation, aerosols and supercooled liquid water, must be a priority in any weather modification experiment. As these variables are usually associated with operational decision making and evaluation of weather modification activities, they should also be measured in operational programmes. Any weather modification experiment or operation should be preceded by the preparation and analysis of climatologies of key variables in order to test the applicability of the weather modification hypothesis to a specific region.

1.10 If it were possible 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 large range of natural variability (low signal-to-noise ratio) and our ability to predict the natural behaviour is still limited.

1.11 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. This situation has been made even more difficult with the potential inadvertent effects air pollution, mega-cities and of agricultural practices on cloud and rain formation. Furthermore, there is mounting evidence that climate change may lead to changes in global precipitation amounts as well as to spatial redistribution of precipitation. Consequently, the use of any evaluation technique must take into account and mitigate the bias introduced by these non-random effects on precipitation.

1.12 Proper evaluation of a weather modification activity requires a randomization process in which only some of the events suitable for seeding are in fact seeded. The accepted process requires the specification of objective criteria for the start of an event, so that bias is not introduced by subjective selection of seeded and unseeded events. Through various statistical techniques (such as regression or double ratio), the impact of seeding is assessed by using the unseeded events to estimate the 'natural' conditions in seeded events. The natural variability of precipitation is so high in many regions that a statistically significant evaluation requires an experiment to extend over many years. The evaluation should involve two stages. The primary analysis is a single test that detects the impact of seeding. The primary analysis is generally a statistical test that provides an estimate of the precipitation increase along with estimates of the statistical significance of the increase and the confidence intervals in which the true impact lies. The primary analysis is supported by a range of secondary analyses aimed at ensuring that the seeding hypothesis was validated. In particular, the secondary analyses provide physical support for the primary analysis, by explaining the scientific basis of the statistical result. The secondary analyses are especially important if the primary analysis yields a null or even negative impact of seeding. The separation of the primary analysis from the secondary analyses is to avoid the statistical phenomenon of 'multiplicity'; that is, if one carries out a large number of statistical tests then by chance one is sure to eventually find a positive result.

1.13 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, draught speeds, concentrations of large drops, ice-crystal concentration, radar reflectivity, cloud top height, and cloud horizontal extent).

1.14 Objective measurement techniques of precipitation quantities are needed for testing weather modification methods. Because each measurement technique has its own characteristic uncertainty, both direct ground measurements (e.g. rain gauges and hail pads) and remote sensing techniques (e.g. radar, satellite) should be considered. Hydrological measurements may be of interest since they are directly related to water management, but are difficult to use since they introduce additional factors such as type of vegetation, slope of the terrain, soil moisture etc. Secondary sources such as insurance data introduce new sources of error and bias, and should not be used by themselves.

1.15 Operational programmes should be conducted in full recognition of the potential risks and benefits 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. Properly designed and conducted operational projects seek to detect and minimize such adverse effects. Weather modification managers should be encouraged to add scientifically-accepted evaluation methodologies to be undertaken by experts independent of the operators. Operational programmes should include physical measurements so the science of weather modification can benefit from the results. In spite of the cautionary notes mentioned above, it should be clear that the potential for increasing rainfall by cloud seeding exists, although the uncertainty of success is still large.

1.16 Brief summaries of the current status of weather modification are given in the following sections. These summaries are restricted to weather modification activities that are based on accepted scientific principles and have been tested in the field.

1.17 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.

1.18 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. through multinational field programmes, independent expert evaluations, education, etc.) are encouraged that could provide the necessary resources for implementing these technologies. Due to the large natural variability it is important to emphasize that weather modification programmes should be viewed a along-term (multi-year) commitment to be able to scientifically evaluate these experiments.

2. FOG

2.1 The relative occurrence of warm and cold fogs is geographically and seasonally dependent. In the past different techniques were used to disperse warm (i.e., at temperatures greater than 0°C) and cold fogs, for instance, at airports and, to a lesser extent, on highways. At present, these are less common, especially at airports with advanced navigation systems that allow landing in low visibility conditions.

2.2 The thermal technique of fog dispersal that employs intense heat sources (such as jet engines) to warm the air directly and evaporate the fog particles, has been shown to be effective for short periods for dispersal of some types of fogs. Also, techniques have been used that mix dry air into the fog using hovering helicopters or ground-based engines. Both the mixing and the thermal technique are expensive for routine use.

2.3 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.

2.4 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.

3. PRECIPITATION (RAIN AND SNOW)

3.1 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

3.2 In our present state of knowledge, it is considered that the glaciogenic seeding of mixed-phase clouds formed by air flowing over mountains offers good prospects for increasing precipitation in an economically-viable manner under suitable conditions. 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.

3.3 Observations supported by numerical modelling indicate that supercooled liquid water can exist in amounts sufficient to explain 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.

3.4 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, targeting of the seeding material, and the times and situations in which it is not advisable to seed, thus optimizing the technique, reducing inadvertent risks and maximizing the cost effectiveness of the operations.

3.5 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 also difficult to target the seeding agent from either ground generators or from broad-scale seeding by aircraft upwind of an orographic cloud system. The accurate and timely identification of regions of sustained supercooled liquid water and the ability to target these regions in often times varying wind conditions with seeding material are critical to the success of these experiments and is often a major challenge.

Synoptic-Scale Cloud Systems

3.6 The seeding of cold stratiform clouds began the modern era of weather modification. Under certain conditions shallow stratiform clouds can be under certain conditions made to precipitate, often resulting in clearing skies in the region of seeding.

3.7 Cloud systems associated with mid-latitude synoptic fronts can contain supercooled liquid water. When these systems pass over mountain ranges, the pre-existing supercooled liquid water can be enhanced, leading to conditions suitable for cloud seeding.

3.8 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

3.9 In many regions of the world, cumuliform clouds are the main precipitation producers. These clouds are characterized by strong vertical velocities with high condensation rates. They hold the largest condensed water contents of all cloud types and can yield the highest precipitation rates. Seeding experiments with cumuliform clouds have produced variable results, which are at least partly due to the high natural variability of convective clouds.

3.10 Because cumuliform clouds can occur in many different conditions, the resulting precipitation can develop through rain drop coalescence (warm cloud) or through ice (cold cloud) processes or in combination of these processes (mixed-phase clouds). Thus glaciogenic or hygroscopic techniques may be used to modify this type of cloud. Precipitation enhancement techniques by glaciogenic seeding are utilized to affect ice and mixed phase processes, while hygroscopic seeding techniques are used to affect warm and mixed phase processes. Evaluation of these techniques has utilized direct measurements with surface precipitation gauges as well as indirect radar-derived precipitation estimates. Rainfall patterns produced by cumuliform clouds have complex spatial and temporal characteristics that are difficult to resolve with rain gauge networks alone.

3.11 The responses to seeding, based on reviews of historical experiments, 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°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. 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.

3.12 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 micrometers in diameter) is used to accelerate precipitation initiation by stimulating the condensation-coalescence process by favourably modifying the initial droplet spectrum at cloud base. Second, seeding with larger hygroscopic particles (about 30 micrometers in diameter) is used to accelerate precipitation development by stimulating the collision-coalescence processes. A randomized experiment utilizing the latter technique indicated statistical evidence of increases in radar-estimated precipitation increases. However, the increases were not as indicated by the conceptual model, but seemed to occur at later times (one to four hours after seeding). The cause of this apparent effect is not known.

3.13 Recent randomized seeding experiments with flares that produce small (0.5 to 1.0 micrometers in diameter) 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, limited physical measurements were obtained suggesting that the seeding produced a broader droplet spectrum near cloud base that enhances the formation of large drops earlier 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.

3.14 Despite some statistical evidence of changes in radar-estimated precipitation changes in individual storms using both glaciogenic and hygroscopic techniques, there is no evidence that such seeding can economically increase rainfall over significant areas.

4. HAIL

4.1 Hail associated with complex and deep convection 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 by focusing on new growth regions of hailstorms.

4.2 While progress has been made, our understanding of storms is not yet sufficient to allow confident prediction of the effects of seeding on hail suppression. Supercell storms have been recognized as a particular problem due to damage cause by these very dynamic and energetic mesoscale systems. Cloud remote sensing and numerical cloud model simulations have provided guidance in our ability to understand the complexity of the hail process and improved our ability to delineate favourable times, locations and seeding amounts for effective modification treatments, but the simulations are not yet accurate enough to provide final answers.

4.3 A few randomized trials have been conducted for hail suppression using such measures as hail mass, kinetic energy, hailstone number and area of hail fall. These randomized trails have not been conclusive. 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. Despite large reductions having been claimed by many groups, the weight of scientific evidence to date is inconclusive and operational programmes should strengthen the physical and evaluation components of their efforts. Significant advances in technology during the last decade have opened new avenues to document and better understand the evolution of severe thunderstorms and hail.

4.4 Anti-hail activities using cannons to produce loud noises (acoustic waves) have neither scientific basis nor credible physical hypotheses.

5. TROPICAL CYCLONES (HURRICANES, TYPHOONS)

5.1 Tropical cyclones (hurricanes, typhoons) 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. Tropical cyclones modification experiments that aimed at reducing the maximum winds were conducted in the 1960s and early 1970s but without positive results. Despite 30 years of subsequent research, there is no generally accepted evidence suggesting that hurricanes can be modified.

6. OTHER WEATHER PHENOMENA

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

6.2 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 has been introduced into thunderstorms. There are also methods to initiate lightning early, thus reducing the electrical charge of the cloud. This is done by rockets with a long wire behind. The chaff is postulated to provide points for corona discharge which reduce 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.

7. INADVERTENT WEATHER MODIFICATION

7.1 Some issues related to inadvertent cloud modification are the same as those involved in creating deliberate changes. Hence, research directed toward understanding of inadvertent cloud modification is closely parallel to that of research to improve the scientific basis of cloud seeding. There is ample evidence that widespread biomass burning and agricultural and industrial activities modify local and sometimes regional weather conditions.

7.2 Land-use changes (e.g. urbanization and deforestation) also modify local and regional weather. Air quality, visibility, surface and low-level wind, humidity, temperature, and cloud and precipitation processes are all affected by large urban areas. Documenting the inadvertent effects of human activities on clouds and precipitation may provide additional insights into the theoretical basis for advertent (deliberate) attempts to modify the weather. In most cases of inadvertent weather modification as opposed to cloud seeding experiments, it is difficult, if not impossible, to determine and differentiate the type of particles that participate in cloud processes unless long-term measurements are available. Cloud seeding could also be used to study the effects of aerosols on clouds by seeding clouds with known particle concentrations and types as has recently been shown in the literature.

8. ECONOMIC, SOCIAL AND ENVIRONMENTAL ASPECTS OF WEATHER MODIFICATION

8.1 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.

8.2 Economic, social, ecological and legal aspects should be taken into account during the design stage of an operation.

8.3 Published studies have shown no significant impact of silver iodide (AgI) used in past weather modification operations either on human health or on the environment. However, any plans to use either a massive quantity of such a product or a different seeding agent should be accompanied with a preliminary evaluation of its potential effects on environment or on human health.

8.4 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. In operational programmes, monitoring of possible environmental effects should be undertaken as a check against anticipated impacts.

8.5 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.

GUIDELINES FOR THE PLANNING OF WEATHER MODIFICATION ACTIVITIES

1. These guidelines are addressed to Members requesting advice or assistance on weather modification activities and should be used with the Statement on Weather Modification. They include recommendations for research experiments 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. Guidelines for research experiments – as well as recommendations for operational programmes are provided. This Statement was revised in response to the request of CAS XV and approved by the CAS Management Group in September 2010.

2. Members wishing to develop activities in the field of weather modification should be aware of the uncertainties outlined in the WMO Statement on Weather Modification.

3. It should be realised that the energy involved in weather systems is so large that it is impossible to create artificially rain storms, alter wind patterns to bring water vapour into a region, or completely eliminate severe weather phenomena. Weather Modification technologies that are claimed to achieve such large scale or dramatic effects do not have a sound scientific basis (eg. hail canons, ionization methods) should be treated with suspicion. The only credible 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.

4. Experimental programmes should be planned on a long-term basis (many years) because the precipitation variability is generally much greater than the increases or decreases claimed for artificial weather modification. Care should be taken in the design of the experiment and to engage qualified operators. It is strongly recommended that an objective evaluation be performed by a qualified group independent of the operational one. The use of appropriate observations and numerical models may help in reducing the time required to evaluate the project.

5. Acceptance of the results of a weather modification programme depends 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, powerful numerical models, and sophisticated statistical techniques.

6. WMO recommends that a detailed examination of the suitability of the site for cloud seeding should be conducted in the way as reported in past WMO reports on weather modification. 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 amenable conditions for weather modification;
(b) Conditions are suitable for the available modification techniques;
(c) Modelling studies support the proposed weather modification hypothesis;
(d) Socio-economic and environmental consideration should be included as an integral part of the design of weather modification research experiments and operational programmes.

7. 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.

8. WMO recommends that cloud seeding projects for precipitation modification be designed to allow statistical and physical evaluation of the results of seeding. If a rigorous evaluation is desired, then some randomization of the seed/control cases should be incorporated. The physical measurements should include characterization of the seeding material. Operational weather modification projects should be reviewed periodically (annually if possible) to assess whether the best practices are being used. Any new project should seek advice from experts regarding the benefits to be expected, the risks involved, the optimum techniques to be used, and the likely impacts. The advisors should be as detached as possible from the project, so their opinions can be viewed as being unbiased.

9. 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) WMO can take no responsibility for the consequences of the advice given by any invited scientist or expert;
(c) WMO accepts no legal responsibility in any dispute that may arise.