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WEATHER MODIFICATION

At the Thirty-third Session of the Executive Committee of the World Meteorological Organization held in Geneva, 1-17 June 1981, a statement was adopted for use as a basis for replying to relevant enquiries on weather modification. The statement appears as Annex II to the "Abridged Report with Resolutions", Thirty-third Session of the Executive Committee, World Meteorological Organization, and is reproduced here for information.

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NEW ZEALAND METEOROLOGICAL SERVICE

WEATHER MODIFICATION

(Foreword from the Director, New Zealand Meteorological Service)

The main WMO activity in weather modification is in the Precipitation Enhancement Project (PEP), which is under control of the PEP Board. The Commission for Atmospheric Sciences (CAS) Working Group on weather modification also acts as the Executive Committe Expert Panel.

There has been a marked lessening of enthusiasm for field weather modification activities, over the last several years, and the emergence of a strong feeling that there is a greater need to learn more about the physics and dynamics of clouds, both from field work and through numerical modelling. There is also a growing realisation that the same resources used for cloud physics work can, with some modifications be used for other atmospheric chemistry/ pollution, radiation, etc., studies.

It is generally agreed that the time is not yet ripe for an international hail suppression programme to be initiated. Although a number of Members do carry out hail suppression work/studies, there does not appear to be a need for WMO to become involved other than in encouraging Members active in this field to co-operate and to allow other Members to collaborate in joint studies.

REVIEW OF THE PRESENT STATUS OF WEATHER MODIFICATION

(Prepared by the WMO Executive Committee Panel of Experts on Weather Modification, May 1981)

Introductory Remarks

It is impractical to modify weather by competing directly with the energies prevailing in the atmosphere, except locally. Instead, points of instability are sought whereby a relatively small disturbance in the system can substantially impact the natural evolution. For example, populations of cloud drops in some layer clouds may persist for long periods without growth or sedimentation. Introduction of giant cloud condensation nuclei or water drops into such a cloud might result in precipitation by causing an accelerating sequence of collisions and growth among the drops. In the case of clouds at temperatures colder than 0°C, the introduction of artificial ice nuclei (e.g. through silver iodide seeding) or ice crystals (e.g. through solid carbon dioxide (dry ice) seeding) can result in the rapid growth of ice at the expense of numerous small supercooled water drops. In addition, the formation and growth of larger numbers of ice particles (by heavy seeding) may release sufficient latent heat to significantly increase buoyancy in the cloud and thereby enhance precipitation.

The ability to influence cloud microstructures in the ways indicated above has been demonstrated in the laboratory, and verified through physical measurements in some simple natural systems such as fogs, thin layer clouds and small cumulus clouds. However, evidence that precipitation, hail, lightning, or winds can be significantly modified by artificial means is quite limited. It is now realized that the complexity and variability of clouds result in great difficulties in understanding and detecting the effects of attempts to modify them artificially. Thus, some of the optimism of the 1950s has given way to a more cautious approach. As knowledge of cloud physics and statistics, and their applications 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 micro-physical and air-motion measuring systems, radar (including Doppler), satellites, raingauge 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 data sets, used in conjunction with increasingly sophisticated numerical cloud models, help in testing various weather modification hypotheses.

Since the effects of artificial seeding on clouds and on precipitation are within the range of natural variability, statistical analysis is generally necessary to provide a measure (in probabilistic terms) of the strength of evidence for or against seeding effects. Although the power and scope of statistical evaluations for analysing cloud seeding effects is steadily improving, pitfalls exist. Statistical evaluations based on randomized experiments are considered the most reliable. In the case of precipitation modification, target/control areas may be suitable if their rainfalls are highly correlated. Multiple control areas may be necessary to assess chance trends in surrounding areas that parallel seeding effects. In most cases, experiments must run for several years to achieve a statistically significant result. Measurements and statistical analysis of variables such as ice particle concentrations, radar reflectivities, precipitation rates in the cloud, rainfall on the ground, in seeded and unseeded cases can serve not only to shorten the time required for conclusions to be drawn from an experiment, but will also provide data to examine the physical plausibility of a result. Background studies in the experimental area are required in order to determine the importance of, and correlations between, variables. Historical statistical comparisons are suspect because they may involve intercomparisons of inconsistent data sets. Also, insurance values and projected crop yields are not considered satisfactory test variables.

Viewed from these perspectives, most of the past weather modification experiments are considered inconclusive by the scientific community. Careful evaluations, involving both extensive physical measurements of the clouds and precipitation and statistical analyses of the measurements are now considered mandatory in arriving at sound judgements. At this time, weather modification other than supercooled fog dispersal must be considered in the realm of research. Enhancing precipitation or suppressing hail reliably and on demand remain distant goals.

Many operational programmes are conducted with recognition of the risks inherent in unproved technology. For example, there are indications that under certain conditions seeding may cause less rain in the target area, or more hail and decreased precipitation accompanying the hail. Unfortunately operational programmes are seldom conducted in a manner that allows scientific evaluation.

Brief summaries of the current status of weather modification in several categories are given in the following section. The general criteria for evaluating the results of cloud seeding will be as outlined in this preamble. Only those weather modification activities are considered that appear to be based on sound physical principles and which have been tested in the field.

The Enhancement and Redistribution of Precipitation from Supercooled Clouds

Many natural clouds are supercooled, in other words they contain liquid droplets at temperatures colder than 0°C. Natural freezing nuclei, present in highly variable amounts, facilitate the freezing of some cloud droplets into ice crystals. These crystals, usually a small minority among all the cloud particles, then grow at the expense of the droplets, and so tend to lead to precipitation of the cloud. If the concentration of the natural nuclei, and thus of the crystals which result, is very small, the process of precipitation can be very slow, and it is in such cases that the introduction of artificial nuclei (typically crystals of silver iodide) is thought to be effective. Such additional nuclei would speed up the process of precipitation in the cloud and augment the amount of precipitation - snow or rain - that falls out of the cloud.

The freezing of cloud water implies the release of latent heat of freezing, and this in turn adds positive buoyancy to the cloud. If there are enough nuclei to freeze all the cloud droplets, the cloud will quickly glaciate (become an ice cloud).

The introduction of artificial nuclei (seeding) is thus motivated by one or more of the following expectations:

- That the precipitation process in the cloud is accelerated and that more cloud water is converted into precipitation;

- That the buoyancy created will have desirable dynamic effects on the cloud;

- That the cloud is glaciated, which may effectively terminate or postpone the precipitation process.

An order-of-magnitude argument may be given for the minimum mass of reagent (for example AgI) that is needed to produce rain in the absence of other nuclei. One gram of silver iodide can be divided into some 10^{14} crystals. Assuming that these can be widely distributed in space, and that each of them becomes the nucleus of a particle which ultimately grows into a raindrop 2.5 mm in diameter, more than a million cubic metres of rain would result. Distributed over an area of 1000 km^2, this would be the equivalent of 1 mm of rain. In the light of this type of argument, and because, in many regions of the world, a large proportion of clouds are supercooled, this seeding technique has attracted the greatest number of attempts at precipitation enhancement.

Several major experiments have been conducted in various types of cloud systems, including orographic, winter convective and summer convective clouds. Some of these have provided either statistical or physical indications that seeding may have affected precipitation. To date only one cloud-seeding experiment has combined physical evidence in support of a seeding hypothesis with persuasive statistical evidence of increases in precipitation over an area. That project, carried out on winter convective clouds in Israel during two consecutive experiments over a 15-year period, resulted in an apparent precipitation increase of about 15 per cent.

There is some evidence that certain subtropical convective clouds become taller and larger when they are heavily seeded to release latent heat. In view of the high correlation between the size of convective clouds and rainfall from them, the seeded clouds presumably give more rain than if they had been unseeded. Confirmation that areal precipitation can be increased in this way is required from suitably designed experiments.

A question that commonly arises is whether seeding in one area to increase precipitation might inadvertently produce changes (decreases are most often mentioned) in precipitation outside of the target area. No firm statistical or physical evidence is available on this point.

There is some physical evidence that deliberate heavy seeding (so-called overseeding) of clouds in certain topographical situations can result in the diversion of snowfall (up to 50 km). However, seeding trials of this type have not been subjected to statistical evaluation.

Modification of Rain from Warm Clouds

In tropical or subtropical countries many potential rain-producing clouds are convective in nature with tops often not exceeding the height of the freezing level. Hence, the possibility of increasing rainfall from such warm clouds by enhancing the efficiency of the collision-coalescence process has generated considerable interest in these regions.

In some warm clouds the development of large droplets may be sufficiently slow to delay the onset of significant growth by collision-coalescence until the cloud has passed its mature stage. In principle it is possible to enhance precipitation from such clouds by seeding them with hygroscopic particles or water drops to hasten the growth process. However, only a limited number of experiments have been carried out to test the effectiveness of these techniques. One problem is that large masses of seeding material are required. For example, if seeding is carried out with 10 μm-diameter salt particles of density 2 g cm^{-3}, and each particle ultimately grows to a raindrop of 2.5 mm diameter, over 100 kg of salt would be required to produce one million cubic metres of rain (equivalent to 1 mm of rainfall over an area of 1000 km^2). Even for this modest result, it has been necessary to assume a more favourable growth ratio than is likely to occur in practice. The situation would be much more favourable if a "chain reaction" occurred in which drops break up after first growing by coalescence to a large enough size, and the fragments then served as growth centres for new large droplets. More direct evidence is needed to establish the importance of such a process in natural clouds. In spite of these limitations, a few encouraging (but not conclusive) experiments have been carried out. None have the requisite combination of successful rainfall increases based on physical and statistical evidence.

Warm and Cold Fogs and Stratus

Certain techniques have been shown to be effective in clearing warm and cold fogs. The most reliable is the thermal method, which employs intense heat sources (such as jet engines) to warm the air directly and evaporate the fog. These systems are expensive to install and to use. Such a system is in operational use at the Orly and Charles de Gaulle airports serving Paris. Another technique that has had occasional utility is the use of hovering helicopters to mix drier air from higher levels to evaporate warm fogs.

Seeding with hygroscopic materials has also been used in attempts to clear warm fogs. Hygroscopic seeding with NaCl, for example, induces the formation of a few drops that, as they settle to the ground, can sweep out many fog droplets. The physical principles upon which these techniques are based are well understood. 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 individual cases. The corrosive properties of some hygroscopic agents may pose problems.

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 where there is a relatively high incidence of supercooled fog. Suitable techniques are dependent upon temperature and other factors. Dry ice has commonly been used. Other systems employ rapid expansion of compressed gas to cool the air enough to form ice crystals. Because large quantities of ice crystals can be generated, which grow and fall out in a few minutes, the logistics of this type of seeding is much simpler than hygroscopic seeding. Because the effects of this type of seeding are easily measured and results highly predictable, statistical verification generally has been considered unnecessary in this case.

Stratus cloud can be thought of as an elevated fog layer; thus most of the airborne techniques applicable to surface fog can be used to make holes in stratus. Very few experiments have been conducted with warm stratus, but clearing of limited areas of supercooled stratus by seeding with dry ice has been demonstrated repeatedly. Questions concerning the range of cloud thicknesses remain that can affect optimum seeding concentrations and delivery patterns, and the achievable extent and duration of clearing.

Hail Suppression

Hail causes considerable damage to crops and property. Consequently there has been, and continues to be, interest in hail suppression throughout the world.

Many hypotheses have been proposed for suppressing hail. The most common rationale has been creating enhanced competition among hailstones and their embryos for available moisture. This hypothesis, also known as "beneficial competition" or the "competing hailstone or embryo hypothesis", can be simply stated as follows.

The number of growing hailstone embryos can be increased to a threshold concentration where competition for the available liquid water prevents the ice particles from growing too large so that the resulting hailstones melt before reaching the ground. It should be noted, however, that unless the critical threshold is exceeded, this technique calling for more numerous embryos would cause more hail.

In order to implement the competition hypothesis by means of seeding with ice nuclei, it appears that production of additional hailstone embryos (to compete with natural embryos for the available supply of supercooled water) in the hailstone growth region of the cloud is the most promising approach. In this case the seeding agent must act when and where the embryos form, which may be at some distance from the hailstone growth region.

Hail suppression operations are conducted in several countries on the strength of many years of favourable results reported in some countries. Strict evaluation of the efficacy of operational hail suppression is complicated by the high natural variability of hail in both time and space. Because of this, it is very difficult to assess the results of either experimental or operational hail suppression programmes unless a very high degree of suppression is achieved, or unless predictor variables or other evaluation criteria can be provided reliably through forecasts. The requisite combination of physical and statictical evidence of hail suppression capability is lacking.

The field of hail suppression has reached the point where further significant advances in application must await the resolution of several key scientific problems. Included among these are improved forecasts of hail occurrence, better understanding of hailstorm structure and dynamics, the origin and growth of hailstone embryos and the evolution in time and space of the hailstone.

Hail suppression activities may be accompanied by changes in rainfall, which could be a factor in assessing economic benefits.

Tropical Cyclone Moderation

Tropical cyclones contribute significantly to the annual rainfall of many areas, but they are also responsible for considerable damage to property and great 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.

A few modification experiments were conducted in the 1960s with the aim of altering the distribution of energy released near the centre of tropical cyclones. The idea was that the latent heat released through heavy artificial seeding with ice nuclei would provide a means changing the location of the major vertical mass transport, which in turn would influence the horizontal wind field.

There is some support for this hypothesis from numerical model experiments, which suggest that such artificially-induced releases of latent heat can cause the old hurricane eyewall to be replaced by one having reduced winds. Model results indicate that the new eyewall circulation may be stable over a significant period, and that if the inflowing air can be induced to rise in enhanced convective updraughts at a radius 80 per cent larger than that of the pre-existing eyewall, maximum winds might be reduced by about 30 per cent.

Several seeding experiments in the 1960s on Atlantic hurricanes are not inconsistent with the hypothesis described above, but wind speed variations occur naturally in tropical cyclones and so the hypothesis of deliberate modification cannot be regarded as proven. Also, measurements made during those past experiments did not allow the links in the suggested physical changes leading to reduced winds to be verified.

In view of the limited data, lack of statistical randomization and the preliminary state of theoretical models, the hypothesis that winds in tropical cyclones can be reduced by seeding has not been proved. However, the encouragement offered by the few observations available, and the prediction of some models justify further experimentation. Operational seeding of tropical cyclones is not recommended until the subject is better understood.

Lightning Suppression

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 (to produce large concentrations of ice crystals) have been introduced into thunderstorms. The chaff is postulated to provide points for corona discharge which controls the electric field to values below those required for lightning, whereas augmenting the ice crystal concentration is postulated to change the charge distribution within the clouds. Field experiments have used these concepts. Results, while encouraging, have no statistical significance.

Economic, Social and Environmental Aspects of Weather Modification

Weather modification is sometimes considered when there is a need to improve the economy of a region by increasing water resources for agricultural use, water supplies for cities, or for hydroelectric power generation. In deciding whether to apply such techniques, it hardly need be emphasized that the benefits of modification should be larger than the costs of a weather modification operation. However, in considering benefits to some segments of the population, losses to other groups must also be weighed, together with possible compensation schemes. For example, whereas one type of crop may benefit from more rain, another may not; more rain may be good for agriculture, but not for a flourishing tourist industry in the same area; bigger crop yields may lead to lower prices and reduced profitability of some farm operations. Thus it is necessary to consider not only the economics of the segment that desires a certain type of weather modification, but the overall net effect on the whole community.

Precipitation enhancement has to be viewed from the overall aspect of total water resource management. It may be difficult or impossible to ameliorate drought conditions when they occur. In most droughts, clouds suitable for seeding are normally scarce. Replenishing aquifers with water (which can be pumped to the surface if needed) or filling reservoirs and augmenting snowpacks is obviously easier because the timing of precipitation is not crucial. Thus, changes in agricultural practices, with conversion to storage and irrigation, may be needed.

Wherever weather modification causes economic conflicts, problems of a legal nature may arise. Besides, weather modification activities within the boundaries of a particular state may be perceived by a neighbouring state as having adverse effects within its borders (the so-called "extra-area effects", that in this case are alleged to go beyond the boundaries of the state carrying out weather modification activity).

Some countries already have provisions for regulating the conduct of weather modification activities, while the international community is developing guidelines for resolving international conflicts arising out of weather modification activities. However, it must be emphasized that weather modification still remains in the realm of research. Any legal system aimed at regulating weather modification at the international level must be developed hand in hand with scientific knowledge in the field.

The implications of any projected long-term weather modification operation on ecosystems need to be assessed before long-term, large-scale operations are undertaken. Such impact studies could reveal changes in the balance of economic benefit. During the operational period, monitoring of possible environmental effects should be undertaken as a check against estimated impacts.