WMO Statement on Weather Modification

FACT SHEET

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***The statement is dated and includes information only up to June 2024, as required by EC-79. It will be updated regularly.**

Weather modification is the deliberate intervention in the Earth's atmosphere to influence local weather conditions, typically through techniques like cloud seeding. This primarily involves dispersing substances into clouds to alter precipitation patterns to increase rainfall, reduce hail, or dissipate cloud cover. The World Meteorological Organization (WMO) neither promotes nor discourages the practice of weather modification. The activities of WMO with respect to weather modification are aimed at encouraging scientifically sound research projects and at guiding best practices for research and operational projects.

The topic of climate intervention, that is deliberate actions taken to mitigate the impact of climate change, is not the focus of this document. Weather modification is focused on local to regional spatial scales and corresponding timescales, while climate intervention is primarily focused on the global scale and climate timescales. While there can be regions of overlap between weather modification and climate intervention (e.g. marine cloud brightening), the purpose of this document is to present the status of weather modification.

It should be realized 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 eliminate severe weather phenomena. Weather modification technologies that claim to achieve such large-scale or dramatic effects do not have a sound scientific basis and should be treated with suspicion.

Hygroscopic seeding adds particles to the cloud with the intent to modify the number and size of liquid drops while glaciogenic seeding targets the number and size of ice crystals. Although cloud seeding technologies for purposes like augmenting precipitation, reducing hail damage, and dispersing fog are still developing, recent research in wintertime glaciogenic orographic cloud seeding has shown significant progress, demonstrating an evidence-based causal relationship for this specific method. One reason for the success of seeding of orographic clouds is linked to the constrained cloud dynamics. In clouds with high dynamical complexity, such as supercells, the signature of seeding is largely masked by the natural variability. Scientific proof on the impact of hail cannons and ionization methods at the cloud scale is still lacking.

Operational programmes in fog dispersion, rain and snow enhancement and hail suppression are taking place in more than 50 countries worldwide. The primary aim of these projects is to obtain more water, reduce hail damage, eliminate fog, or other similar practical results in response to a recognized need. The 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 benefits, but uncertainties in the effect of the modification make investments in such efforts subject to considerable risks. Meanwhile, demand for these weather modification activities is increasing steadily due to the incidence of droughts and other calamities.

Continuing strategic research is required to observe, investigate, and explain the scientific hypotheses on which weather modification is based. As 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, early warning systems and climate change adaptation. With a sound scientific understanding of the relevant atmospheric processes, a weather modification experiment can be designed and implemented to test the feasibility of the activity and the validity of the underpinning scientific hypothesis and to provide the basis for operational activities. Strategic research should also go beyond traditional atmospheric science studies and incorporate the interdisciplinary aspects to address the end-to-end needs of the weather modification activity, such as hydrological, economical, and water management, social science and policy research.

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

Proper evaluation of a weather modification activity has several requirements. For a statistical evaluation, first, it needs to include a randomization process in the experimental design based on a physical hypothesis such that only some of the events suitable for modification are treated. This requires objective criteria defining the start of an event so that bias is not introduced by subjective selection of events for treatment. Second, in the “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/decrease 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” to validate the seeding hypothesis. New evaluation methods have recently been developed that include high-resolution numerical modelling. For numerical model-based evaluation methods to be accepted, uncertainties in the model need to be quantified and the simulations should be constrained by observations to the greatest extent possible.

Published studies have shown no significant impact on either human health or on the environment from silver iodide (AgI) or other commonly used seeding agents used in past weather modification operations. However, any plans to use either a significantly greater quantity of such a product or a new seeding agent should be accompanied by an evaluation of its potential effects on the environment and human health.

Unintended consequences of weather modification, including downwind effects and environmental and ecological impacts, have been suggested in some studies, but need further investigation as part of any weather modification effort.

There is mounting evidence that human activities affect local and sometimes regional cloud properties and precipitation (examples are megacities and ship tracks). Clarifying the existence and processes of such inadvertent (unintentional) weather modification may provide important insights into the possibilities and limitations of deliberate (intentional) 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 mesoscale and cloud processes unless long-term measurements are available.

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

Fog

In principle, all types of fog can be dispersed by sufficient heating or mechanical mixing, though such methods are often impractical and expensive. Thus, any trials of fog dispersal should thoroughly investigate the prevailing thermodynamic conditions and the specific factors contributing to fog formation, ensuring a comprehensive understanding before any seeding intervention.

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

Precipitation

There is considerable evidence that cloud microstructure can be modified by seeding with either glaciogenic or hygroscopic materials under appropriate conditions. The criteria for those conditions vary widely with cloud type.

Glaciogenic cloud seeding is used on supercooled liquid and mixed-phase clouds to induce ice-phase precipitation. There is statistical evidence, and physical evidence from 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.

Hygroscopic cloud seeding is applied to the liquid phase portion of clouds with the intent of promoting the collision and coalescence of water droplets, which in turn will lead to a greater precipitation efficiency. Commonly, convective clouds with complex dynamics and large natural variability in precipitation are the target of hygroscopic seeding. This large natural variability creates a weak signal-to-noise scenario, which complicates gaining statistically significant results in the primary analysis.

While some peer-reviewed recent cloud seeding trials, both glaciogenic and hygroscopic, have reported enhanced precipitation, results depend on natural cloud characteristics. Results from one trial cannot be directly applied to a different environment. In some historical experiments, the results have even been inconsistent with the original seeding hypothesis. More research and observations are required to better quantify the environmental conditions favourable for and the potential to modify these clouds.

Alternate techniques for precipitation enhancement remain highly controversial in the scientific community. The community generally remains sceptical on such techniques. Considerably more research is needed before these methods should be further considered.

Hail

In many parts of the world, glaciogenic seeding technologies continue to be used operationally in an attempt to mitigate hail damage. In many of these efforts seeding targets new growth zones of mature hailstorms or so-called feeder clouds. In some projects, where hailstorms were classified into several types depending on their power and stage of development, and a static assessment of the effectiveness was carried out separately for each group, a reduction in the size of hailstones was reported. In several projects, it was found that the weaker the hailstorms and the earlier it was seeded, the faster the changes in cloud characteristics were achieved and the faster it was possible to affect hail. However, experiments on seeding hailstorms are clearly not yet sufficient to convincingly accept the scientific postulates and concepts underlying this technology, due to the high energy, dynamics and natural variability of these storms.

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

Other Phenomena

There is no generally accepted evidence suggesting that tropical cyclones (hurricanes and typhoons) can be modified.

There are no demonstrated methods to modify tornadoes, lightning strike danger, floods, and other severe weather phenomena by cloud seeding.

General Comments

The scientific status of weather modification continues to advance, yet it still reflects our limitations of the detailed understanding of cloud dynamics and microphysics and precipitation formation. Additionally, there are inadequacies in accurate in-situ and remote measurement of cloud liquid and ice particles and any ensuing precipitation. To address these challenges, governments and scientific institutions should significantly enhance their efforts in basic physics and chemistry research related to weather modification. This can be achieved through a significant focused thrust on quality-controlled observations and numerical modelling as well as advancing through data science techniques. 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 number of well-executed experiments and building the base of scientific results. International collaborations, for example under the auspices of WMO, both in observations and numerical modelling can substantially enhance the credibility of such experiments.

Significant challenges in public, social, and local acceptance are widely evident including in relation to considerations of ethics and environmental justice. Governments, scientific institutions, and international collaborations should enhance their efforts in exploring social science including: the framing of weather modification, resulting impacts on policy formation and public/stakeholder participation, and economic considerations.

Governments and other agencies involved in weather modification activities should invest in relevant education, training, and capacity development through local and international opportunities. Governments and other agencies should also invest in relevant social science exploring the weather modification project and activities in the context of social science considerations.

It is recognized that most weather modification projects are motivated by welldocumented requirements, but they may also have associated risks and the results 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 and WMO should be kept informed on all weather modification activities.

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- Weather

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