
Planned and Inadvertent Weather Modification

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1. Introduction

Humans modify the weather deliberately and unintentionally; this is well founded in both theory and observations. Evidence accumulated over the last 40 years suggests that certain local weather conditions including fogs, low clouds, and precipitation in some areas can be altered by carefully controlled cloud seeding. Similarly, the effects of inadvertent weather modification are becoming better understood. Cities and industrial complexes affect local weather conditions and alter precipitation. Regional weather changes result from other human activities such as deforestation and vehicle traffic on major transportation corridors. The focus of this statement is limited to local and regional changes and is mainly concerned with the scientific background to the problem. The Society's policy on global climate change is separate and has previously been presented (*Bull. Amer. Meteor. Soc.*, ***72,*** *57*).

Early cloud seeding efforts, conducted in the 1940s and 1950s, involved attempts through field operations to increase precipitation without a sound scientific foundation. Most early scientific cloud seeding experiments were designed, conducted, and evaluated on the premise that statistical analyses of one or more variables (primarily precipitation) would yield statistically significant and scientifically acceptable results. Data from many experimental seasons were often required to achieve sufficient numbers of test cases. Results of such experiments have been mixed, some showing increases, some decreases, and many no statistically significant changes. Most of these experiments lacked supporting physical documentation as to how precipitation increases, if any, were achieved. In addition, the lack of clear cut replication of the more successful cloud experiments has diminished their credibility and value. Thus, satisfactory determination of the capabilities of cloud seeding to produce desired effects under various conditions has not resulted from the statistical analyses.

Developments have expanded our abilities to understand and document precipitation processes. For example, the development of microwave radiometers and their application to the measurement of supercooled liquid water (SLW) has revealed the existence of low altitude SLW within winter orographic clouds above the crestlines of mountain barriers. Aircraft-based sensing platforms often fail to detect low-level SLW because aircraft cannot safely fly sufficiently close to the mountain barriers.

Vertically pointing radiometers sited at or near barrier crestlines have often observed quantities of SLW sufficient to give useful additional snowfall if successfully precipitated by cloud seeding.

Multiparameter radars, which can distinguish between liquid and ice-phase hydrometeors in clouds, offer new prospects for remote sensing of seeding signatures. Such radars have been successful in differentiating regions of graupel and hail from rainfall.

Complementing such physical measurements, demonstration seeding trials have confirmed seeding effects from both aerial and ground-based releases. Observations of increased ice-particle concentrations in seeded air volumes also tagged with tracer gases such as sulfur hexafluoride have increased confidence that observed effects follow from efforts to stimulate precipitation.

Furthermore, recent advances in computer hardware, software, and physical understanding have allowed improvements in two- and three- dimensional numerical models which simulate cloud processes. These models continue to provide an ever-improving understanding of the complicated interactions within both natural and seeded clouds. Numerical simulations are now able to replicate many of the details observed in actual clouds. The impacts on cloud and precipitation development resulting from slight variations in cloud microphysical or dynamic characteristics can be produced for the same cloud, for both natural and seeded circumstances. This is the only manner in which identical clouds can be studied in both treated and untreated versions, which may lead to more confident prediction of seeding effects and thus improved selection criteria for candidate clouds.

Similarly, our ability to assess inadvertent modifications of our atmospheric environment has also improved. Atmospheric changes that might have passed unnoticed, or have been dismissed as inconsequential just a few years ago, are now often found to have broader ramifications. Some of these changes are quite subtle; for example, increased cloudiness associated with condensation trails from jet aircraft may modify the radiation budget at the ground. Others, such as acid rain are more obvious; structures, vegetation, and lake water quality have all been adversely affected. Air quality and visibility are often locally degraded by increased anthropogenic pollutants, and urban effects on temperature, humidity, wind, and precipitation have been well documented.

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2. Status of planned weather modification

There is growing evidence that glaciogenic seeding (the use of ice-forming materials) can, under certain weather conditions, successfully modify supercooled fog, some orographic stratus clouds, and some convective clouds. Recent research results, utilizing both in situ and remote measurements in summer and winter field programs provide dramatic though limited evidence of success in modifying shallow cold orographic clouds and single-cell convective clouds. Field studies are beginning to define the frequencies with which responsive clouds occur within specific meteorological regimes.

Successful treatment of any suitable cloud requires that sufficient quantities of appropriate seeding materials must enter the cloud in a timely, well-targeted fashion. As the need for stringent spatial and temporal targeting has been established, it has become apparent that problems with seeding plume delivery in many early experiments may in part account for the failure of such programs to produce significant results.

a. Fog and stratus removal

Operations employing glaciogenic seeding to dissipate supercooled fog and low stratus have become routine at some airports. The ability to admit more solar radiation to reduce heating requirements through the dissipation of such clouds and fogs appears promising.

The dissipation of warm (nonsupercooled) fogs can often be accomplished by more expensive thermal techniques, but this has proven cost effective at only a few major airports. More reliable and economical warm-fog dissipation techniques have not yet been established.

b. Precipitation increase

There is considerable evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of precipitation records from some long-term projects indicate that seasonal increases on the order of 10% have been realized. The cause and effect relationships have not been fully documented; however, the potential for increases of this magnitude is supported by field measurements and numerical model simulations. Both show that SLW 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 recently been directly observed during seeding experiments conducted over limited spatial and temporal domains. While such observations further support statistical analyses, they have to date been of limited scope, and thus the economic impact of the increases cannot be assessed.

Recent experiments continue to suggest that precipitation from single-cell and multicell convective clouds may be increased, decreased, and/or redistributed. The response variability is not fully understood, but appears to be linked to variations in targeting, cloud selection criteria, and assessment methods.

Heavy glaciogenic seeding of some warm-based convective clouds (bases about +10°C or warmer) can stimulate updrafts through added latent heat release (a dynamic effect), and consequently increase precipitation. However, convincing evidence that such seeding can increase rainfall over economically significant areas is not yet available.

Seeding to enhance coalescence or affect other warm-rain processes within clouds having summit temperatures warmer than about 0°C has produced statistically acceptable evidence of accelerated precipitation formation within clouds, but evidence of rainfall change at the ground has not been attained.

Although some present precipitation augmentation efforts are reportedly successful, more consistent results would probably be obtained if some basic improvements in seeding methodology were made. Transport of seeding materials continues to be uncertain, both spatially and temporally. Improved delivery techniques and better understanding of the subsequent transport and dispersion of the seeding materials are needed. Current research using gaseous tracers such as sulfur hexafluoride is addressing these problems.

There are indications that precipitation changes, either increases or decreases, can also occur at some distance beyond intended target areas. Improved quantification of these extended (extra-area) effects is needed to satisfy public concerns and assess hydrologic impacts.

Precipitation augmentation programs are unlikely to achieve higher scientific credibility until more complete understanding of the physical processes responsible for any modification effect is established and linked by direct observation to the specific methodology employed. Continued research emphasizing in situ measurements, atmospheric tracers, a variety of remote sensing techniques, and multidimensional numerical cloud models that employ sophisticated microphysics offer improved prospects that this can be accomplished.

c. Hail suppression

The efficacy of projects intended to mitigate the severity of hailstorms remains indeterminate. Statistical assessments of certain operational projects indicate successful reduction of crop hail damage, but scientific establishment of cause and effect are incomplete. Results of various operational and experimental projects provide a range of outcomes. Some suggest decreases in hailfall, but others have produced inconclusive results, and some suggest increases. Given the diversity of conceptual models, cloud seeding criteria, seeding agents, delivery techniques, assessment methods, and the storms themselves, this is not unexpected. It is a direct reflection of storm complexity as well as the spatial and temporal variability of hail.

Statistical evaluations using hail characteristics (i.e., kinetic energy, hailstone size, and area of hailfall) have often yielded inconclusive or inconsistent results. Historic trends in crop hail damage have been used to evaluate many operational programs, but these data can be unreliable and so must be used cautiously.

Our understanding of hailstorms is not yet sufficient to allow confident prediction of the effects of seeding individual storms, and the most appropriate seeding methodology has not been determined. The possibility of increasing or decreasing both hail and rain in some circumstances is recognized, but numerical cloud models have recently affirmed that the desirable outcome, that is, a decrease in hail and an increase in rain, is possible.

Hail results in significant economic losses worldwide; thus, research on hail suppression continues. As with precipitation augmentation efforts, increased in situ observations, remote sensing (e.g., multiparameter radar), and numerical cloud modeling capabilities continue to improve our understanding of hailstorms as a foundation for more effective scientific endeavors to suppress hail.

d. Severe storms mitigation

There is no generally accepted conceptual model for modifying tropical disturbances. Hurricane modification experiments of the 1950s and 1960s were inconclusive. Although strong interest continued into the 1970s, no organized research effort was undertaken, and few studies have been devoted to this subject for the past 20 years.

No sound physical hypotheses exist for the modification of tornadoes, or of damaging winds in general, and no scientific experimentation has been conducted. Experiments have been carried out to suppress lightning but have not yet yielded methods sufficiently developed for application.

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3. Status of inadvertent weather modification

There is ample evidence that agricultural and industrial activities modify local and sometimes regional weather conditions. Urbanization also results in localized weather modification. Air quality, visibility, surface and low-level winds, humidities and temperatures, and cloud and precipitation processes are all affected by large urban areas.

a. Impacts of agricultural practices

Variations in cropping and irrigation practices are known to alter local albedos, humidity, surface temperatures, and roughness. Large-scale irrigation projects alter boundary-layer conditions, increasing the potential for precipitation. Overgrazing of large grasslands and large-scale deforestation reduce evapotranspiration and change the surface roughness, altering the moisture, temperature, and winds in the boundary layer and causing a net loss of precipitation.

b. Urban effects

Surface temperatures in urban areas are higher than those in adjacent rural surroundings. This heat island effect, coupled with increased roughness and urban structures, alters local winds and atmospheric circulation patterns leading to convergence zones which initiate clouds and precipitation under certain atmospheric conditions.

Combustion of fossil fuels increases atmospheric particulates and aerosols over and downwind of major cities. This reduces air quality and visibility and also influences the local development of clouds and precipitation.

Major cities with populations in excess of 1 to 2 million, and located in continental climates, influence warm-season clouds and increase precipitation by 10%–20%, with a lesser effect on precipitation in cold seasons. Recent studies of urban areas in tropical regions have confirmed that significant modification of weather conditions also occurs in this climatic zone leading to cloud and precipitation increases.

c. Atmospheric influences from industrialization

Atmospheric effluents from manufacturing and power generation facilities add significantly to aerosols and trace gas constituents, increasing smog and degrading visibility. Ingestion by clouds of some emitted gases (e.g., sulfur dioxide, SO_2) results in the production of acidic precipitation, which can, in sufficient concentrations, adversely affect structures, vegetation, and water quality. Large cooling lakes and cooling towers cause localized fogs, low clouds, and icing under certain weather conditions.

d. Effects of large-scale transportation corridor

Condensation trails from jet aircraft often persist and in areas of frequent flights sometimes spread, creating cirrus and/or cirrostratus cloud decks. These reduce insolation and can lead to lower surface temperatures. The resulting cloudiness is most frequently found along major airport corridors of the United States and Europe. The jet-induced cloud tracks can persist for many hours or even days. Traffic in major surface transportation corridors result in sizable releases of effluents (NO_x's and other particulates) which affect regional visibility and degrade air quality.

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4. Environmental and societal impacts of weather modification

The impacts of weather modification on society can be far reaching. Therefore, the ecological, hydrological, socioeconomic, and legal ramifications of such activities must be considered and assessed. The complexity of the effects of altered weather have been found to lead, in most cases, to both benefits and problems in various societal sectors and environmental areas. Wise use of planned weather modification should recognize this varying distribution of effects and plan to assess the impacts in the design, operation, and evaluation of field projects. There may need to be compensation for those affected negatively and liabilities must be assessed and understood where possible, to inform the public and those who make decisions relating to the use of weather modification. Many stated have enacted laws that regulate the use of weather modification, and the federal government requires that all weather modification projects be reported annually.

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5. Recommendations

The prospect of being able to predictably modify fogs, clouds, and precipitation in certain conditions requires continued assessment of planned weather modification techniques. Much is known about the physical processes involved in many aspects of inadvertent weather modification, but important questions remain, including those relating to large-area irrigation projects and major transportation corridors. 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. However, many measurements within and near clouds are required to test and improve the models. More effort must be made to obtain these, not just for sounder weather modification but for large-scale weather and climate prediction and other uses, such as the remote sensing of precipitation.

As socioeconomic factors place increasing demands on finite water resources, the demand for viable weather modification methods will logically increase. The following tasks summarize the most pressing questions:

1. The physical processes and specific conditions under which it is possible to increase, decrease, or relocate precipitation should be fully defined. The degree of change possible must be quantified to establish whether economic benefits can be realized. The use of untested weather modification techniques during severe droughts, as a means of increasing precipitation, is not recommended. Opportunities to increase precipitation are typically minimal during droughts and only well-tested techniques should be considered, realizing that only limited precipitation augmentation will probably result.
2. Hail suppression concepts should be reexamined, refined, tested, and (if necessary) modified to determine whether conditions exist under which hail can be suppressed.
3. The extent of impacts produced by inadvertent weather modification requires improved definition. Further atmospheric studies are needed of cities of varying types and in different physical settings to better understand and predict local and regional-scale weather influences from ever-growing urbanization, and to investigate the potential larger-scale atmospheric influences of major transportation corridors and extensive irrigation areas.The extent of impacts produced by inadvertent weather modification requires improved definition. Further atmospheric studies are needed of cities of varying types and in different physical settings to better understand and predict local and regional-scale weather influences from ever-growing urbanization, and to investigate the potential larger-scale atmospheric influences of major transportation corridors and extensive irrigation areas.

More complete understanding and documentation of the physical processes involved in both deliberate and inadvertent weather modification is needed. These are challenging tasks requiring well-focused, long-term efforts. Breakthroughs in any of these areas are unlikely; progress will more probably continue to be evolutionary.

Increasing population, shifting demographics, and the prospect of global climatic change require that water resources be managed to best alleviate the chronic shortages that are already beginning to manifest themselves. Thus, the economic feasibility of cloud modification methods needs to be determined. Likewise, actions that inadvertently modify weather or climate need to be better understood, quantified, and (if necessary) mitigated.

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