PRESENT AND FUTURE OF WEATHER MODIFICATION: REGIONAL ISSUES

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INTRODUCTION

This paper 1) reviews potential weather modification technologies, 2) speculates about the applicability of these technologies in various regions of the United States, and 3) estimates the efforts needed and likely time required to get technologies operational throughout the United States. A weather modification technology is defined as a proven, workable system of altering clouds or precipitation in a prescribed way. The technology is defined to include: 1) the seeding materials, 2) the seeding delivery system, 3) how these two systems have been intermeshed for use on the basic weather types, and 4) expected results of the seeding. Technology includes the design of an operational program and the means of evaluating the results, but the latter subject is not included in this paper because the many and complex means of evaluating weather modification have been recently reviewed in detail (Changnon, 1975).

A short review of the two major principles for weather modification is presented initially so as to set the stage for the discussion of actual technologies (seeding agents and delivery systems). These two sections together serve as the background material for the three major portions of this paper. The first of these deals with the potential technologies as they relate to four weather classes: convective storms, non-convective precipitation systems, fog, and hurricanes. Both rain enhancement and hail suppression are treated within the convective storm class. The second section treats translation of weather modification to regions and other nations and illustrates existing and potential problems. The final section is an outlook as to the future research needs with estimates of time intervals before technologies will be available for nationwide application.

REVIEW OF MODIFICATION PRINCIPLES

Before reviewing the potential technologies for modification of rain, hail, fog, and hurricanes, it is well to consider briefly the principles for cloud and precipitation modification. The major existing principles have been classed as 1) colloidal instability, and 2) dynamic effects. Other principles involving lesser used and less well-established means for cloud dissipation, cloud formation, and precipitation redistribution exist, but are not considered herein.

Altering colloidal stability. The physical basis for most weather modification operations has been the belief that seeding with certain elements would produce colloidal instability in clouds, either prematurely, to a greater degree, or with greater efficiency than in nature. Most cloud seeding presumes that at least a portion of the treated cloud is supercooled, that nature is not producing any or enough ice at that temperature of the cloud, and that treatment with chemical agents or refrigerants will change a proportion of the cloud to ice. The resultant mixture of water and ice is unstable and there is a rapid deposition of water vapor upon the ice and a simultaneous evaporation of water from the supercooled droplets in the cold part of the cloud. The ice crystals so formed become sufficiently large to fall relative to remaining droplets, and growth by collection enhances the probability that particles of ice or water will grow to be large enough to fall from the cloud and become precipitation.

This process of precipitation enhancement using ice nucleants has been demonstrated for the stratiform type cloud, and generally for those which are orographically-produced and supercooled. Cumulus clouds in a few regions of the United States have also been examined for the potential of colloidal instability in their supercooled portions. This has been founded on beliefs that precipitation 1) can be initiated earlier than by natural causes, or 2) can be produced from a cloud which was too small to produce precipitation naturally.

Seeding in the warm portion of the cloud, or in "warm clouds" (below the freezing level), has also been attempted so as to alter their colloidal instability. Warm-cloud seeding has primarily attempted to provide the large droplets necessary to initiate the coalescence mechanism, and is of value in clouds where insufficient large drops exist. In general alteration of the coalescence process primarily precipitates out the liquid water naturally present in a cloud, whereas the ice-crystal seeding process also causes a release of latent energy that conceivably results in an intensification of the storm, greater cloud growth, and additional precipitation.

Altering cloud dynamics. The effects to alter the colloidal instability of clouds, or their microphysical processes, have been based on the concept of rain increase through increasing the precipitation efficiency of the cloud. Simpson and Dennis (1972) showed that alterations of cloud size and duration by "dynamic modification" could produce much more total rainfall than just altering the precipitation efficiency of the single cloud. In relation to cumulus clouds, "dynamic seeding" simply represents alteration one step beyond that sought in the principle of changing the colloidal stability. In most dynamic seeding efforts, the same agents are introduced into the storm but often with a greater concentration, and in the conversion of water to ice, enormous amounts of latent heat are hopefully released producing a more vigorous cloud which will attain a greater height with accompanying stronger updrafts, a longer life, and more precipitation. Seeding to produce dynamic effects in cloud growth, whether stratiform or cumuliform types is relatively recent at least in its serious investigation, but it may become the most important technique. If through controlled cloud seeding additional uplift can be produced, the productivity in terms of rainfall will be higher whether the actual precipitation mechanism involved is natural or artificial.

It has been proposed that the selective seeding of cumulus clouds also can either a) bring upon a merger of two or more adjacent clouds and a much greater rainfall production through a longer-lived, larger cloud (Simpson, 1973), or b) produce eventually an organized line of clouds (through selective seeding of randomized cumulus). The latter could allegedly be accomplished by minimizing and organizing the energy into a few vigorous systems rather than a larger number of isolated clouds (Hosler, 1969).

Essentially, then, 'dynamic seeding' is a label addressed to processes involved in altering cloud microphysics in a selective and preferential way to bring upon more rainfall through an alteration of the dynamical properties of the cloud system leading to the development of stronger clouds and mesoscale systems. Actually, dynamic effects might be produced in other ways such as alterations of the surface characteristics to release heat, by the insertion of chemical materials into dry layers of the atmosphere to form clouds, or by redistribution of precipitation through microphysical interactions in cloud processes.

WEATHER MODIFICATION TECHNOLOGY

Seeding materials. Materials that have been employed for altering rain, hail, fog, and hurricanes have all functioned, at least initially, to alter the cloud microphysical processes. In general, minute amounts of seeding materials, relative to the volume of in-cloud materials, have been used with the expectation that 'proper amounts' and delivery to the 'proper portion' of the cloud will essentially bring about a "triggering" effect at a critical place and time. Thus, it will produce a result much greater than the ratio of the seeding material to the cloud material. Essentially, a series of rapid multiplicative reactions are the hope of most weather modification techniques and materials.

The seeding materials most frequently used have been classed and sorted according to whether they were 1) generally hygroscopic materials used to alter the coalescence process in the warm part of the cloud, or 2) were ice nuclei, used to enhance nucleation in the supercooled part of the cloud.

Enhancement of cloud coalescence by water spray was attempted in the 1950's (Braham, et al., 1957). Results from the use of large amounts of sprayed water in a cloud, 450 gal/mi, were fairly spectacular. It is a technology that has not been adequately developed, probably because of the expense of the large aircraft needed to carry and dispense large volumes of water into cumulus clouds. Water spray has also come into use as a material for modification of warm fogs, those forming at temperatures >0°C. The second important material used for alteration of the coalescence process (hygroscopic seeding) is salt (Na Cl). Finely powdered salt particles have been used in many weather modification experiments in the United States and abroad. Some key problems have concerned determining the best particle size to use and developing the instrumentation to produce this size and to control the spray. Salt has also been used in warm fog seeding efforts.

Other attempts at producing coalescence, either in clouds or fog, have dealt with means of artificial electrification. Chemicals believed to enhance droplet combination by electrical forces (polyelectrolytes) have undergone tests for the dissipation of warm fogs. Arrays of charged wires at the surface have been used to produce corona discharges so that the ions produced by the discharge will attach to natural dust particles for transportation to the clouds, but evidence that this enhanced precipitation formation has not been offered.

Artificial glaciation of clouds in their supercooled portions has been produced by various materials. The first experiments proved that the injection of Dry Ice into the area of a cloud below freezing (or in a supercooled fog) produced enormous numbers of ice crystals in the cloud. Dry Ice, like the use of water seeding to produce coalescence, suffers from the need for aircraft capable of high altitudes (above $0^{o}C$) and for proper equipment to produce pellets of controlled sizes. However, these problems do not affect its use in the suppression of supercooled fog.

The other principal way to induce glaciation in supercooled fogs or clouds is by artificial ice nuclei. The most commonly used material is silver iodide which has a crystal structure that closely resembles that of ice. Lead iodide is also a good artificial ice nuclei, but in the United States it is not used because of its potential toxic properties. Many weather modification programs have employed silver iodide introduced in the form of smoke by generators or by pyrotechnic devices. Principal problems have included the fact that 1) the optimum amounts of silver iodide for a given type of experiment (cloud) have not been well-established, 2) that sunlight with time reduces the nucleation effectiveness of silver iodide, and 3) that silver is not a desirable material if brought down in large quantities into water and soils. Other forms of ice nucleating materials have come from organic compounds. Primary among these organic compounds has been the fertilizer, urea. Urea acts to produce glaciation, even at temperatures slightly warmer than freezing and might enhance coalescence in both warm cumulus clouds and warm fogs. More experimentation is needed, but urea would not be considered to have any undesirable surface effects when brought down in rainfall.

Delivery systems. The other major aspect of the weather modification technology concern those means whereby the previously described materials are delivered into the "critical" portions of the clouds where alterations of the microphysics and dynamics are desired. The means of delivery and diffusion of the materials into this critical area and diffusion within it have varied widely.

In general, delivery systems can be put into two classes: 1) indirect air transport involving use of atmospheric motions both to transport the materials to the critical area or zone and then to diffuse it within it, and 2) the direct delivery approach involving placement of the material in the critical area, often with a built-in means of diffusing the material within the critical volume of the cloud or fog area.

Indirect atmospheric transport methods are those that have been most widely employed because of various problems of technology, expense, and flight regulations. Ground-level delivery systems have been widely employed because they are the most inexpensive of the delivery systems. Some form of generator is used to emit the seeding materials. Ground-based systems are often adequate for fog suppression, depending upon the specific area and the existing weather conditions such as wind direction and speed. However, the ground-based delivery system for the modification of clouds, in the absence of mountains where the cloud base and the ground are close, is fraught with three general uncertainties. First is the great uncertainty as to whether the seeding material released at the ground ever reaches the portion of the cloud where environmental air is entering the cloud (and if so, by what amount). Second, is the great uncertainty as to the potential targeting of the seeded rainfall because of the unknown and variable motions of the seeding material and the clouds affected by this material. The third problem is the question of deactivation of the seeding material between its release at the surface and its entry into the cloud. This deactivation problem is a critical one with respect to silver iodide as the active nucleants produced deactivate in sunlight by an order of magnitude in about 60 minutes.

A second, more meaningful means of indirect atmospheric transport of seeding materials is through use of devices carried on aircraft flown below, around, or above clouds (or above fog). In these instances, the seeding materials are dispensed by a variety of devices (pyrotechnics, generators, grinders, etc.) and allowed to mix with atmospheric currents entering the clouds (entrainment from the sides, updrafts from the bottom, or just gravity from the top) with an expectation that it will reach the critical area of the cloud through the surrounding and in-cloud atmospheric motion. Obviously, this has scientific advantages over the ground-based approach, but it is much more expensive and still does not result in an explicit delivery of materials to the critical area of the storm cloud system, except in the case of fog.

The direct delivery systems involve the insertion of seeding materials into the critical part of the cloud. In some instances, remote sensing devices have been used to delineate the critical part of the cloud and then some form of delivery to that area is performed. Artillery and ground-based rockets are used in the Soviet Union, Yugoslavia, and other Eastern European nations to deliver the seeding materials (lead iodide or silver iodide) into the critical parts of the clouds.

Some efforts have been extended in the United States to use small air-to-air rockets delivered by aircraft. In most of these systems (devices), the material used is partially diffused in the critical cloud area by the ignition and burning of the device.

A relatively new direct technique involves the use of high-flying aircraft which either penetrate the cloud or fly above the cloud and drop devices which burn and dispense the seeding material into the critical part of the cloud. It should be noted that the ground-based direct delivery systems (artillery and rockets) are unlikely systems for use in the United States with its large volume of private and commercial aircraft. Pseudo-direct systems have included ground-based explosive rockets used in Europe and Africa to hopefully shatter hailstones in lower portions of the clouds (Morgan, 1973).

REVIEW OF RESULTS FOR MAJOR WEATHER TYPES

Progress, problems, and findings in the use of the varying weather modification techniques to alter basic weather types including convective storms, non-convective precipitation, fog, and hurricanes are illustrated next. A few of the existing findings for varying kinds of precipitation classes (such as isolated cumulus clouds versus organized lines of clouds) within these weather types are presented to reveal the state of the science and their likely regional applications. Most attention is directed to the issues of modification of convective storms since they produce most of the warm season rainfall and severe damaging local storms that impact on the agriculture and water resources in the eastern two-thirds of the United States.

Convective storms - Rain enhancement. The techniques having the most promise for rain enhancement from convective clouds have largely been developed for single, isolated types of convective clouds. The techniques have been explored largely through experimentation with isolated mountain-type storms (Dennis, *et al*., 1974) or with the isolated semi-tropical storms (Simpson and Woodley, 1971). Almost all aforementioned seeding materials and delivery systems have been employed in efforts to enhance rain from the isolated convective storms. Extrapolation of these results to enhance rain in the isolated, air-mass convective clouds and storms in the marine and continental types of climate of the eastern two-thirds of the United States appears reasonable, but not proven. However, research in Illinois (Huff, 1971) and in Pennsylvania (Hosler, 1969) has indicated that the isolated convective storms produce only a relatively small (10 to 20%) proportion of the total warm season rainfall and presumed increases from such clouds would be inconsequential. Grant, *et al*. (1974) have further shown that in six randomized projects (2 in Colorado, 1 in North Dakota, 2 in Arizona, and 1 in Missouri) attempting to increase convective rainfall from all convective clouds over an area (not just individual clouds), all have produced negative results. This strongly suggests that past techniques are not adequate for area and thus multi-cloud situations.

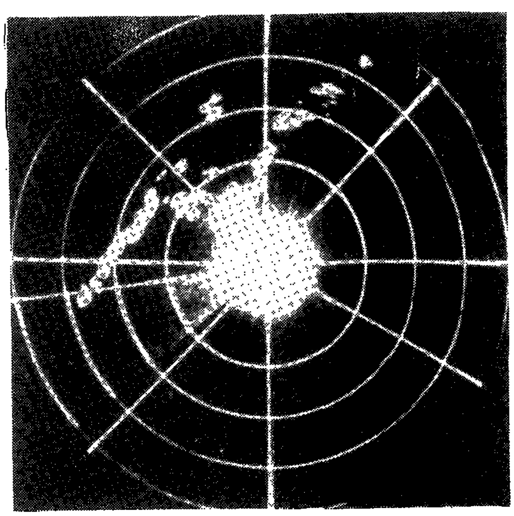
Techniques for seeding and enhancing the principal rain-producing convective storms east of the Great Plains, which are multi-cellular, often complex convective systems, are not established. Ackerman, *et al*. (1971) in a study of precipitation types in the Midwest have shown that there are at least four forms of organized convective storm systems, each with its own peculiar behavior, size, storm density-frequency, and motions. Examples of different forms of organized multi-cellular systems common to the eastern two-thirds of the United States with their associated synoptic weather appear in Fig. 1. Little is known about which seeding technology to use (materials or delivery system) with each of these types of systems. These complex conditions are additionally difficult for weather modification approaches because of the large amount of nocturnal convective precipitation that they produce in the central and eastern United States. Many existing airborne techniques of delivery currently in use are not readily adaptable to nocturnal operations which require complete non-visual remote direction of the seeding system.

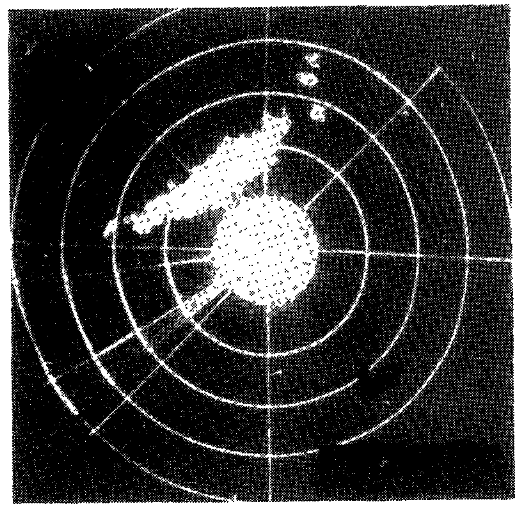
Results from the cumulus seeding projects in South Dakota, Florida, and Missouri (Simpson and Dennis, 1971) have shown certain indications of potential success in multi-cellular groups. However, the research from each of these locations, which are those in or near to the eastern two-thirds of the United States, show a challenging common denominator.

First, the 5-year Missouri seeding experiment (Braham, 1971) showed an overall rain decrease from the randomized seeding of all summer convective storms. Importantly, the only rain increase came on days when there were moderate-sized cumulus clouds (echo tops less than 40,000 feet), and on days with cloud tops greater than 40,000 feet, there was a substantial decrease produced in the area mean rainfall. The South Dakota seeding result, when classed as to those on "shower" days and those on "storm" days showed an increase in area rainfall on the "shower days" (small, semi-isolated convective storms), but no increase on "storm days" (big convective clouds) with an overall rain increase of 10% (Dennis and Kocielski, 1969). The Florida project results (Simpson and Woodley, 1971) show rain increases with both single clouds and merged cloud situations, but these could not be accomplished on "rainy days", as defined by those days when at least 50% of all warm season rainfall occurs.

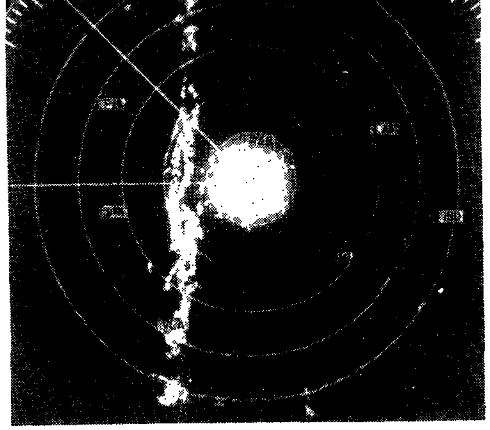
Thus, the best existing results that could be considered as possible predictors of convective rain enhancement in the eastern two-thirds of the United States indicate the likelihood of a) an apparent capability to enhance small isolated convective storms on days when there is not too much natural precipitation being produced, and b) an inability to produce measurable rain enhancement over an area of $\geq$ 1000 km^2, on days of sizable clouds and major natural rain production. Indeed there is evidence that on such days current seeding techniques may decrease area mean rainfall (Grant, et al., 1974). Thus, prospects for precipitation enhancement on those types of days when major convective activity exists, and most of the warm season rain is produced east of the Great Plains, are uncertain. Dynamic seeding leading to mergers of clouds usually appears to be the most favorable technology for attempting the enhancement of precipitation from the predominating multi-cellular storm situations, and experimentation should be pursued in this area with this technique.

However, a critical question exists. Can cloud mergers and the development of multi-cellular systems occur without undesirable side effects? In other words, such systems created to get useful seasonal rainfall

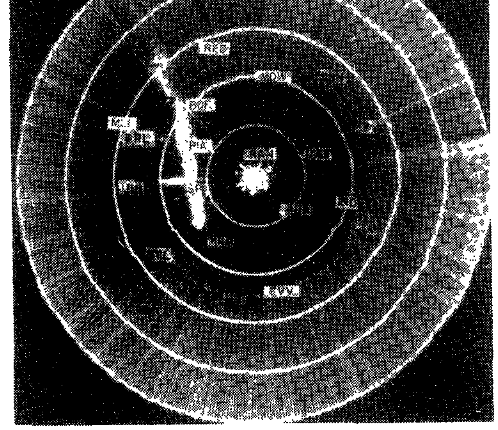




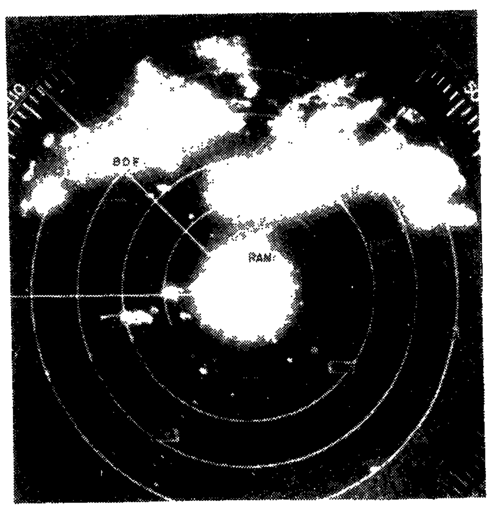
PRE-COLD FRONTAL SQUALL LINES



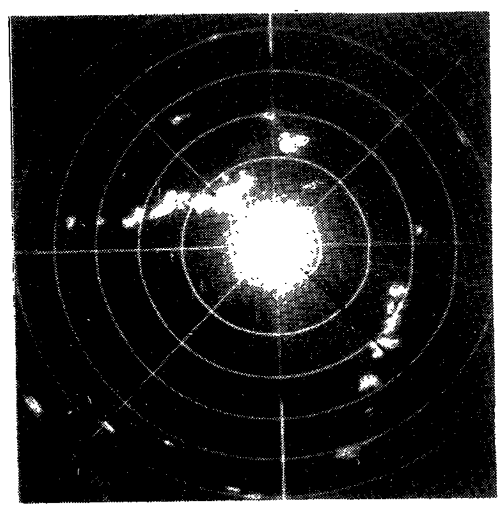
LINE OF ECHOES ALONG COLD FRONT



WARM FRONTAL SQUALL LINE



LINE OF ECHOES ALONG WARM FRONT



LINE OF ECHOES ALONG STATIONARY FRONT WITH A RELATED FRONTAL SQUALL LINE

Figure 1. Examples of different forms of organized multicellular lines of echoes, as defined by related synoptic weather conditions

increases, may also yield damaging hail and severe winds. Studies of inadvertent rainfall modification by cities such as St. Louis (Changnon, 1973b) suggest that the urban effects lead to cell initiation with subsequent storm enhancement through cell mergers. The resulting areas of increased rainfall are also often experiencing comparable increases in thunderstorms, hailstorms, and heavy short-duration rainstorms.

In summary, weather modification technologies do not exist for enhancing precipitation from the multi-cellular convective storms that produce 60 to 90% of the warm season rainfall in the eastern two-thirds of the United States. Development of a modification technology for these systems will require major research and experimental efforts. Conversely, the technologies do appear adequate for use with the simple isolated convective storms often produced by orographic effects in the western one-third of the United States. However, these produce less than 20% of the warm season total rainfall east of the Great Plains and 10 to 25% increases in their rainfall would have little significance.

Convective storms - Hail suppression. The results from various hail suppression programs are less certain than those for enhancement of rain from convective clouds, and are best labelled as 'contradictory'. Hail suppression activities have been pursued for a number of years in the Soviet Union, France, Switzerland, Italy, Canada, and the United States (see Fig. 2). The Soviet results appear most promising with 60 to 80% reductions claimed, but, in general, further testing under scientifically controlled conditions appears necessary before their conclusions, or those from elsewhere, can be accepted by the scientific community. Experimentation in North America, largely confined to North Dakota, South Dakota, Colorado, and Canada, has involved several different seeding technologies, but all have largely concerned attempted suppression of hail in the generally isolated daytime storms of mountain origin.

Two basic approaches have been taken towards hail suppression. Most common has been intensive, high rates of seeding of the potential storm with silver iodide in an attempt to transform nearly all of the supercooled water into ice crystals, or to "glaciate" the upper portion of the clouds. However, if only part of the supercooled water is transformed into ice, the storm could actually be worsened since growth by accretion is especially rapid in an environment composed of a mixture of supercooled drops and ice crystals. Importantly, to be successful, this frequently-used approach requires massive seeding well in advance of the first hailstone formation. It is the approach that is being used in Canada, Texas, and the Dakotas.

The second major approach has been used in the Soviet Union and is also being attempted in the National Hail Research Experiment in Colorado. It involves massive seeding with silver iodide, but only in the zone of maximum liquid water content of the cloud. The hope is to create many hailstone embryos so that there will be sufficient supercooled water available to enable growth to damaging stone sizes.

Another approach that can be classed in the potential, little-used

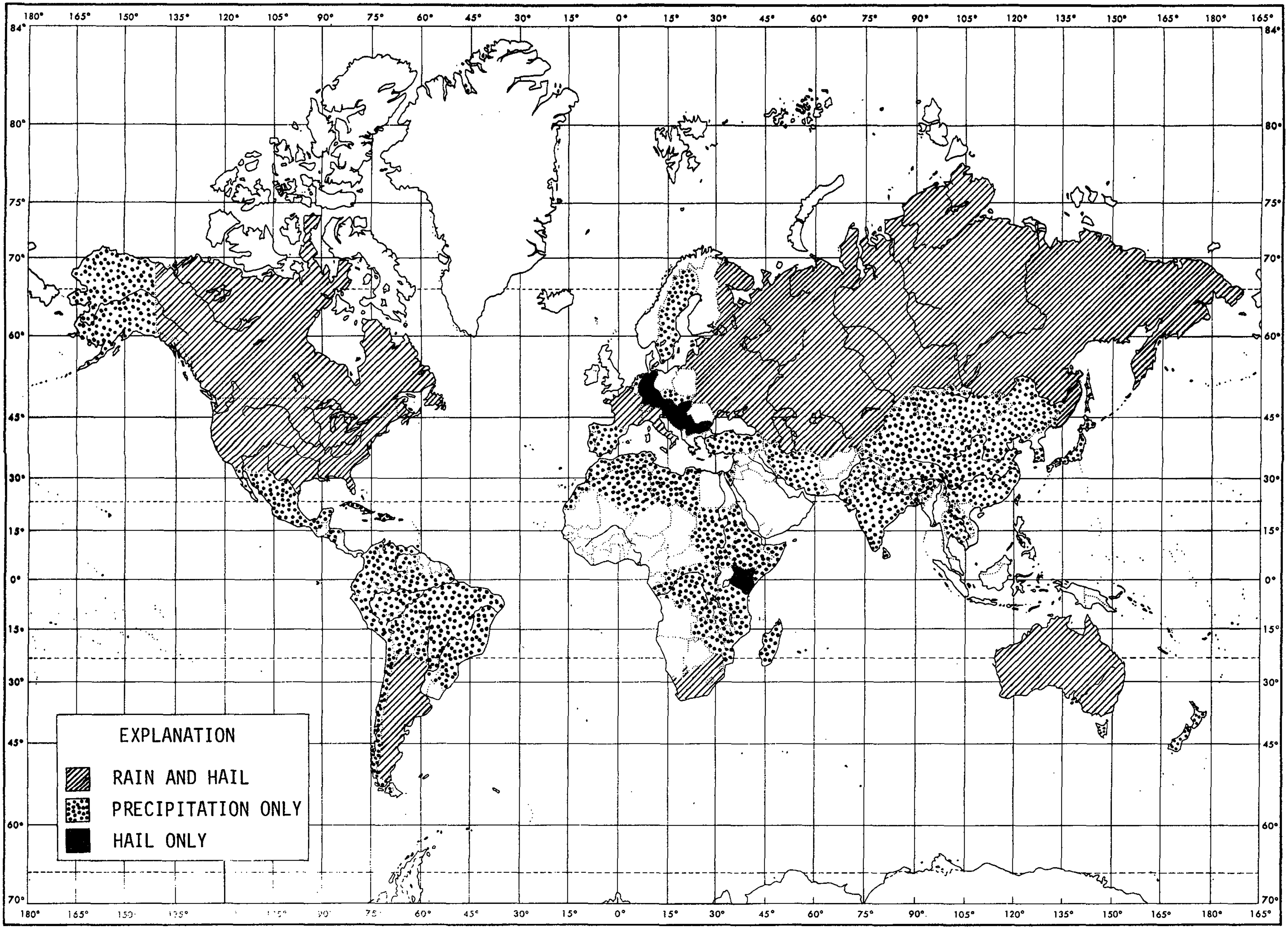


Figure 2. Nations in which Weather Modification (rain enhancement or hail suppression) has been employed during all or portions of the 1946-73 period

category involves seeding a potential hailstorm with large hygroscopic nuclei to produce a large number of large droplets. Upon freezing, these compete with the natural hailstone embryos for the available supercooled water and ideally no stones grow to damaging size. Such seeding could be done with salt and potentially in the updraft of the storm. In one Soviet project this salt seeding is combined with ice nuclei (silver iodide) seeding in the higher (below 0°C) portions of the storm.

Essentially, then, several seeding approaches have been offered, and testing to evaluate these technologies is in progress. Results from the Canadian experimental project suggest 1) success in suppression of hail in the smaller, less complex storms, but 2) no success in the more organized, larger multi-cellular hailstorms. Results of a 4-year experimental suppression project in North Dakota (Miller, et al., 1974) have shown a 60% reduction in crop-hail loss that is significant at the 0.92 confidence level. Operational (non-experimental) hail suppression projects in Canada, the Dakotas and Texas that all involve the first suppression approach and cloud-base seeding have claimed success, although suitable proof is not yet available. If one assumes that the techniques currently under evaluation in North America for seeding of isolated relatively uncomplicated thunderstorms prove successful, these technologies may likely be translatable to the high hail loss regions of the northwestern United States and in the Carolinas. In these two areas, high hail losses come from relatively small uncomplicated convective storms that do not produce large hail and losses occur because of high susceptibility to damage of the fruit and tobacco crops common in the two areas (Changnon, 1972).

Little of a concrete nature can be said about the translation of available hail suppression technologies to the central United States. As with convective precipitation in these areas, most hail comes from the complex, multi-cellular storm systems illustrated in Fig. 1. To further complicate the situation, many major damaging hailstorm systems in the central United States frequently move hundreds of miles and persist with an intermittent nature for 2 or 3 days (Changnon, 1962). They also produce 30 to 40% of their hail at night. Hence, a technology for truly successful hail suppression throughout the Midwest will eventually require a mobile detection and seeding system which can operate at all hours of the day.

Lightning is another thunderstorm hazard that has been investigated for suppression possibilities. Some tests have been carried out by seeding thunderstorms with metallic chaff to produce a current to neutralize the electrical field (Kasemir, 1974). Other tests in Montana have relied on ice crystal dipoles produced by silver iodide seeding from cloud-bases. Results are inconclusive and a technology to prevent lightning is still in the early stages of development (Appleman, 1969).

Non-convective precipitation - Layer clouds. Technologies for enhancing precipitation from layer clouds normally appearing with large-scale cyclonic storm systems, generally present during the colder half year in the United States, are not established. Seeding of such layer clouds with freezing nuclei could conceivably result in the production of precipitation sooner than nature would provide through seeding of the supercooled layer before the natural ice crystals processes become effective. The primary value of enhanced precipitation from these systems, particularly in the eastern two-thirds of the United States, would be to increase surface water supplies, to cover winter grain crops with snow, and to increase soil moisture. Particular value from successful precipitation enhancement in these systems would accrue during the severe multi-year droughts that occur occasionally in eastern North America. It appears necessary to employ a seeding technology involving the use of airborne delivery because of the lapse rate inversion generally associated with overrunning in these situations would prevent surface generated seeding agents from rising to the supercooled cloud levels. If a successful technology could be developed for these storms at any one experimental site in the eastern two-thirds of the United States, it would be translatable to all other regions in the area.

Orographic clouds. Experiments and operational projects involving seeding of winter-time orographic clouds in Colorado and California have indicated that their seeding with ground-based silver iodide generators can cause substantial changes in snowfall, ranging up to 10 to 30% under certain conditions. Experimentation in other western areas hopes to reveal those specific weather conditions during which increases can be obtained. More experimentation in various areas of the west is needed, but the potential for this technology appears to be evolving for most of the major mountain range areas of the United States.

Supercooled fog. There are two basic types of fog, each requiring a different approach to suppress it. Supercooled fog and stratus consits of liquid droplets colder than freezing. Although supercooled fogs are not the common type in the United States, accounting for only 5% of all fog occurrences, they are prevalent in selected northeastern and northwestern parts of North America. The dissipation of supercooled fogs has become an operational weather modification technology. "Cold fog" suppression, largely at airports, has been accomplished by the use of aircraft which fly over the fog and drop various freezing agents, commonly crushed Dry Ice or silver iodide, which initiate ice crystal formation and lead to the precipitation of the growing crystals.

Warm fog. The large balance of North American fogs are "warm fogs" and have tended to defy practical modification. Numerous schemes have been attempted, and they fall into four categories: 1) heating of the air to evaporate the fog (a system initiated during the World War II and called FIDO), 2) drying of the fog with chemical agents, 3) mechanical mixing of the fog with surrounding drier air, and 4) enhancing droplet coalescence by electrical or mechanical means. The heating approach using aircraft engines has indicated some success. Electrical techniques (polyelectrolytes) used on fogs appear to have a chance for success along with spraying of water droplets dispensed from a tube or an airplane. Salt particles acting as hygroscopic nuclei have been dropped into fogs, but there are difficulties such as the development of a technique for obtaining the right salt particle sizes. Means of mechanical mixing have included the use of large helicopters flying above the fog. It appears likely that one or more of these techniques or versions thereof, will come into an operational posture within the next five years, and with some slight modification they will be translatable to most locales in North America.

Hurricanes. Research into the techniques of modification of hurricane winds and other major tropical storms is underway. Efforts to attack the complex problem involve numerical modelling approaches to stimulate the approach and results. Since a hurricane contains huge quantities of supercooled water, seeding with ice nuclei (silver iodide) carried by aircraft conceivably can produce some effect in the storm. Seeding of a few hurricanes with silver iodide has suggested some minor, short-lived changes in the wall cloud of the hurricanes and resulting diminishment in wind speed, but nothing conclusive can be ascribed to the potential for hurricane modification. The complexities of the problems of hurricane modification and the enhancement of large cyclonic storms makes technologies for them appear to lie several years in the future. Successful modification of such storms would seem to have widespread applications and benefits, but certain complex impacts, such as also altering the useful rain produced by hurricanes over the southeastern United States point to the immense social, legal, and economic problems that modification of such large systems could produce.

GEOGRAPHICAL TRANSLATION OF WEATHER MODIFICATION AND RELATED REGIONAL ISSUES

Translation. Through study of the translation of weather modification results and existing technologies from one area to another in the United States would be a very difficult, in-depth effort. This paper does not attempt to delve into this particular problem on a sophisticated regional scale for many reasons, but rather to illustrate some of the translational problems. One of the confusing aspects about convective clouds that leads to difficulties in regional comparisons of results and in translating potential seeding technologies for different regions concerns the various means used to describe and classify convective storms across the United States. In one simple classification, as employed herein, has only three regional-type classes: 1) the mountain-bred convective storms considered basically to be isolated; and in the flatlands of the eastern United States, basically either 2) isolated types or 3) the multi-cellular complex types. However, review of the studies of convective storms reveals many other classifications subtitles including those based on those areas of the storms where the storms have indraft air entering the storm. Studies in some geographical areas, and of some synoptic weather classes, reveal a class based on air entering the rear base of the storm; others on the base sides of the storm; others in the front base; and others at the middle levels of the storm. All of these are important to understand with regard to indirect delivery techniques which depend upon indraft air taking the seeding material to the 'critical part' of the storm.

Another phase of this storm classification confusion concerns the degree of storm organization and often incorporate confusion over the definition of what is a cell. The regional differences between "isolated" single cells, conglomerates of single cells, organized multi-cellular storms, and cases of two or more multi-cellular lines are not defined on a common comparable basis creating a lack of understanding of results between different studies. Other confusing points relating to the classification of convective storms include the direction of their motion and the elevations of their cloud base and height. Within this conglomerate of misunderstanding also occurs an oft-used synoptic weather typing approach. For instance, the "air mass" (non-frontal) storm in one area may actually be classed in a frontal storm situation elsewhere. It should be realized that in most climatic zones of the United States each of these many storm classes can exist. However, the lack of uniformity in their study to determine their frequency and to classify them on a regional scale has been and will continue to be a major factor restricting a clear understanding of regional differences in convective storms. This obviously limits in-depth assessments of the translatability of seeding technologies developed in one area to another area.

The translation of weather modification also can include the entire earth. Again, a complete investigation of the technologies and times of use in each region of each nation would be a massive, if not impossible undertaking.

A simple measure of the global scale transferability of weather modification was developed by determining all nations which have used planned weather modification efforts since the end of World War II, the beginning of the era of modern weather modification. Information was gleaned from a variety of sources including persons with extensive, long backgrounds in weather modification. Information was collected on only rain enhancement and hail suppression projects.

The nations which have experienced some form of rain enhancement or hail suppression using reasonably scientific methodologies are listed in Table 1. Weather modification projects have existed in 62 nations and 48 of these have been totally devoted to rain enhancement programs. Nine more have had both rain and hail projects, bringing the total to 57 nations with some rain enhancement. Fourteen nations have had some form of hail suppression projects.

These 62 nations are also indicated on Fig. 2. Every continent except Antarctica has had rain or hail suppression projects since 1946. Thompson (1965) has shown that severe droughts in the major grain-producing nations around the world (USA, USSR, China) tend to occur in the same time periods (19-teens, 1930's, and 1950's), and the next major global droughts may lead to widespread near global desire and use of weather (rain) modification.

The problem that hail represents in the mid-latitudes of the southern hemisphere has resulted in suppression attempts in Argentina,

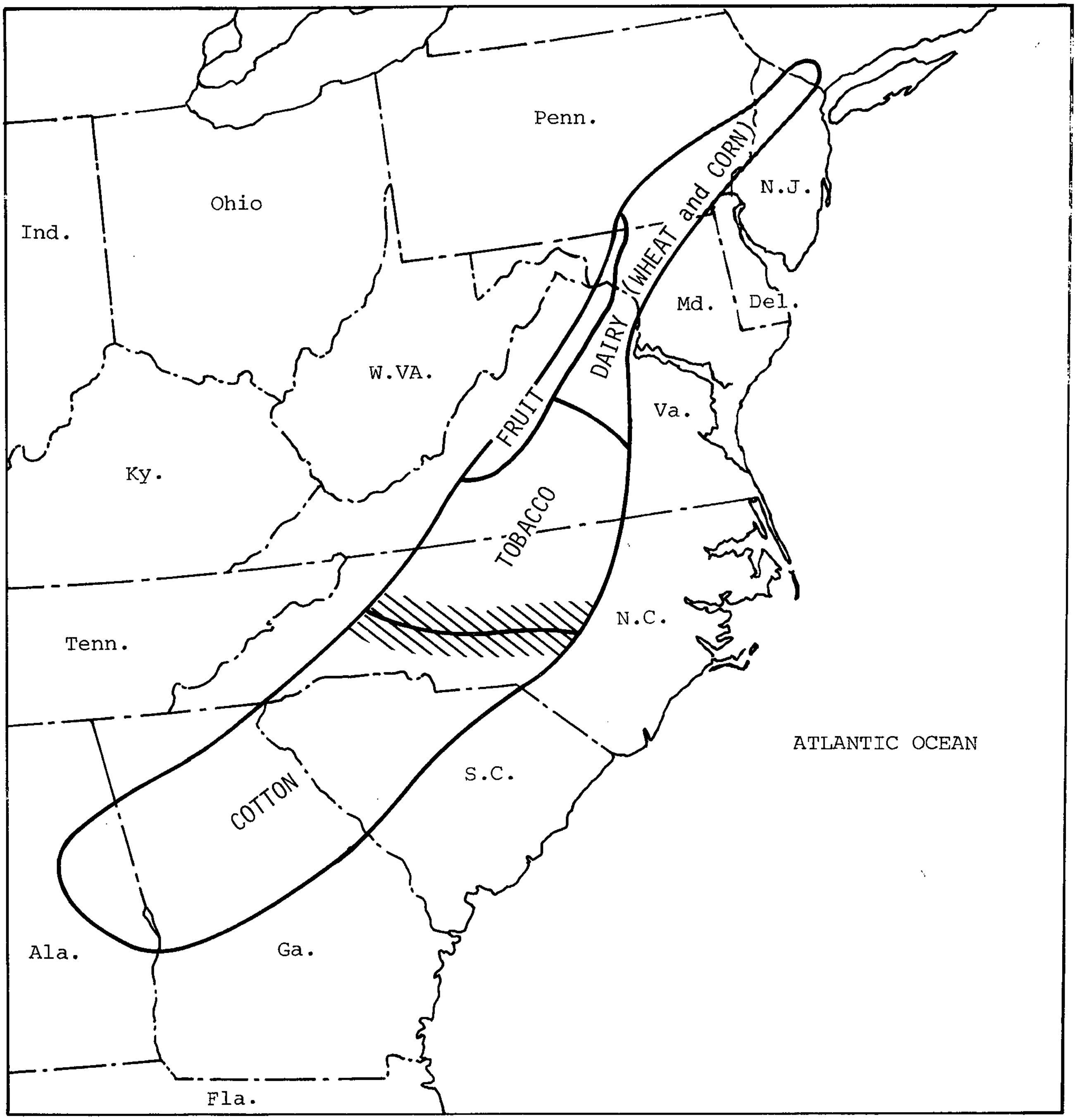


Figure 3 Piedmont Region and Predominant Crop Type

TABLE 2. Outlook for planned weather modification in United States

	Fog	Orographic Precipitation	Convective Rainfall	Severe Convective Storms	Cyclonic Scale Storms
Cold Temperatures (>32^{o}F)	•Operational phase •Low Cost •Research declining	•Operational phase (+10 to +30%) •Low Cost •Research declining	•Research phase •Favorable on small clouds •Questionable on large clouds and systems •Substantial research	•Research phase •5-10 years before operational •Substantial and increasing research	•Exploratory phase •More than 10 years •Research on tropical is modest •Research on "other" storms is minor
Warm (>32^{o}F)	•Research phase •2-5 years •Substantial and increasing research	•Possible phase ← questionable economic value unless chain reaction is found → •Little research	•Exploratory phase •Modest research		
Degree of Complexity (in relation to fog)	1.0	10	100	1000	10,000

Australia, and South Africa. Many northern hemisphere nations in Europe, the Soviet Union, Canada, and the United States have also employed hail suppression projects.

TABLE 1. List of Nations where rain or hail modification has occurred in the 1946-73 period.

Rain Only

Algeria, Azores, Belgian Congo, Brazil, Bolivia, Cambodia, Ceylon, China, Czechoslovakia, Chile, Colombia, Cuba, Cyprus, Dominican Republic, East Africa, Ecuador, Ethiopia, Formosa, French Equatorial Africa, French West Indies, Honduras, Haiti, India, Iran, Israel, Japan, Korea, Libya, Madagascar, Mexico, Morocco, Netherlands, New Zealand, Nigera, Pakistan, Peru, Puerto Rico, Phillipines, Rhodesia, Somalia, S.Rhodesia, Spain, Sudan, Sweden, Tanganyika, Thailand, Tunisia, Turkey, Uganda, Venezuela.

Rain and Hail

Australia, Argentina, Canada, France, Italy, S. Africa, Switzerland, USA, USSR.

Hail Only

Bulgaria, W. Germany, Hungary, Kenya, Yugoslavia.

Another factor not revealed on Fig. 2 concerns the American involvement in this global spread of weather modification. Most of the weather modification projects in South America, Africa, and Southeast Asia were accomplished by American companies or with American financial or technological support. Certainly, the projects in European nations and a few other well-to-do nations (Japan, Russia, Israel) often have involved their own scientists and technologies, but many of the nations displayed in Fig. 2 have employed American companies and expertise on their projects.

Regional applications. There seems little question that a capability to suppress severe storms (hail, tornadoes, winds), would be uniformly accepted throughout North America, if the technology existed and if it did not result in the alteration in the amount of precipitation produced by the storms. However, questions and uncertainties have existed as to whether additional precipitation was useful in the large North American agricultural areas east of the Great Plains. These areas have generally been classed as "humid", and except for occassional droughts, are considered by most to have adequate rainfall.

However, recent studies involving comparisons of crop yields and rainfall have shown that 10-30% increases in growing season precipitation in the eastern United States would produce measurable (5 to 15%) increases in yields of many major crops (Huff and Changnon, 1972). This is further supported by the fact that irrigation of most of the major crops of the eastern United States has developed greatly in the past 20 years. These results indicate that there is a value and potential desire for additional moisture through rain enhancement in the eastern United States.

Location of where water would be beneficial and where conflicts of interest might develop through crop differences in time of water, needs to be considered. Basically, a brief consideration of this problem requires certain assumptions. First, is the fact that the major benefit of precipitation enhancement in the eastern United States would be to agriculture with little significance for the betterment of water supplies. Secondly, that no conflict in an agricultural area due to rain modification would occur if only one major crop is grown.

In general, two or more crops exist in most parts of the United States because certain physical and economic factors both allow and simultaneously dictate their presence. The controlling physical factors in any area include the soil, topography, elevation, and climate, and the climatic factors involve both temperature and rainfall. Normally, there is one dominant crop in a region with an important secondary crop, and in many regions one finds shifts of their importance with changing climate. The important point is that two or more crops are often grown in the same locale which means that they both are basically adaptable to the rainfall regime of that region. However, the crops in an area may differ somewhat in the timing of their growth needs for water. For example, peanuts are grown successfully in the Cotton Belt although they need less water than cotton (U.S. Dept. Agriculture, 1955). Soybeans and corn are grown together in the Midwest, but corn is a) more responsive to rainfall, and b) the periods when the two crops must benefit from rain varies by 2-4 weeks (Changnon, 1965). More classic examples of weather conflicts are in areas where there is cattle raising and garden crops or where hay and other forage crops are grown with grains, and a distinct no-rain period is needed to harvest hay when rain is valuable to the grain crops.

Thus, two kinds of crop-related conflicts relating types to weather and rainfall can be envisioned: 1) areas that have two crops that need distinctly different wet (or dry) conditions at the same time, and 2) areas that adjoin and each features quite different crops such as grains or tobacco nestled against fruit or vegetable crops. Modification efforts in the first situation will have to be sufficiently sophisticated to be "adjustable" to the temporal needs. Operational adjustments based on year-to-year variations in the crop-growth seasons (and water need periods) will be essential. Economic loss considerations due to conflicts must be envisioned and support for seeding must not come from growers of just one type of crop. In a sense, solution for conflict-free rain modification addresses itself to local-regional support and control so as to properly decide upon the seeding efforts during potential conflict periods.

In the second case of potential conflict where crops of differing water needs adjoin, seeding may have to be a) eliminated entirely, or b) be capable of some regional restriction. A specific example of this situation might be a region lying in the Piedmont of the eastern United States. The Piedmont is a rolling hill area of elevations ranging from 100 to 1500 ft. msl and is a distinct geophysical region between the Atlantic coastal plain to the east and the Alpalacian Mountains to the west. It does not have a uniform climate because of its great north-south extent, and the climatic variation particularly helps to divide the Piedmont into sub-regions. The average annual precipitation is relatively high, ranging form 40 (north) to 50 (south) inches per year. A distinct separation exists between the cotton region and tobacco region, as shown on Fig. 3. Tobacco requires abundant rainfall throughout the growing season in this area from April to October, but none at its November harvest. The adjoining cotton needs low rainfall both in spring and fall when too much rain affects the fibre quality and retards picking. The fact that adequate rainfall does not exist is reflected in agricultural figures which show that in 1954 more than 12,000 acres of tobacco land in the Piedmont were irrigated, representing more than 2% of the total crop in the area (USDA, 1965). Cotton in the Piedmont is also irrigated. Irrigation is an analog for rain enhancement, and thus irrigation in the Piedmont indicates rain enhancement might profitably increase yields of both crops. However, crop needs for rainfall in the spring and fall differ. Thus, rain modification along the shaded area marked in Fig. 3, where the two Peidmont crop regions adjoin, could become an area of conflict over weather modification.

The complexity of different crop type regions found in many parts of the eastern United STates could result in many regional conflicts over rainfall enhancement, unless rainfall enhancement could be done by means of a not yet existing, very sophisticated, areally-controlled technology.

RESEARCH NEEDS AND RECOMMENDATIONS

Established technologies for modifying significantly (defined as economically useful) the rainfall and severe weather storms over the more populous and major agricultural areas of the eastern United States do not exist. If measurable economic gains are to be realized in the eastern two-thirds of the United States due to weather modification (largely rain "management", hail suppression, and abatement of severe winter storms), much more research and effort must be extended. This research will concern 1) the thorough study on a regional scale of the complex multicellular convective systems which are the major warm season rain and hail producer, and 2) the study of the cold season cyclonic systems. In both cases, these need to be studied as to how they can be altered hopefully to enhance their precipitation as needed and to alter their undesirable features as needed.

Table 2 is a review and general outlook on weather modification for all the five major types of classes of storms and sorted on their temperature regime. This table also presents a classification of whether the

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modification is in a potential, exploratory, research, or operational phase. Also indicated is the general amount of current research.

An important factor to consider is that success in weather modification and particulary that relating to the convective clouds (whether isolated or grouped) is dependent upon 1) the existing weather conditions (degree of instability, dry layers aloft, amount of shear, etc.), 2) on the extent and size of the existing clouds, 3) on the type of seeding technology employed (the material and delivery systems), and 4) on the existing nuclei concentrations. The growth of understanding in these conditions and in the intelligent experimentation with weather modification can conceivably result in an identifiable means of modifying convective clouds to secure large area beneficial increases in precipitation or decreases in hail. This can only occur when such national goals are set and adequate research investments are made.

Current limited and no-growth federal budgets for weather modification make it appear likely that technologies to modify either the multicellular convective system or the cold season cyclonic systems are at least 10 years in the future. Once technologies are established, imaginative thinking will be needed to design and operate the "movable" seeding systems needed to modify both of these large and moving types of precipitation systems. Until a major commitment is made in the United States to understand and to learn how to modify over large areas, these two kinds of precipitation systems common to the eastern two-thirds of the United States, weather modification will never be a technology of major importance to the United States.

ACKNOWLEDGEMENTS

The assistance of Donald Moore, Archie Kahan, Thomas J. Henderson, Eugene Bollay, and Griffith M. Morgan in helping to compile the list of nations where weather modification has occurred is appreciated. Lewis Grant also assisted in developing the results shown in Table 2. This study was partially conducted as part of Societal Utilization effort of the Applied Research Directorate of the National Science Foundation under grant GI-37859, and as part of the Department of Interior, Bureau of Reclamation contract DI-7197.

REFERENCES

Ackerman, B., S. A. Changnon, G. M. Morgan, and R. G. Semonin, 1972: Precipitation Management in the Midwest: An Initial Review. Special Rept. to Bur. of Rec., Illinois State Water Survey, Urbana, 22 p.

Appleman, H., 1969: An Introduction to Weather Modification. Air Weather Service Tech. Rept. 177, Belleville, Illinois, 38 p.

Braham, R. R., and J. R. McCarthy, 1971: Project Whitetop - Results and Interpretation. Proc. Int. Conf. on Wea. Mod., Amer. Meteor. Soc., Boston, pp 127-129.

Changnon, S. A., 1962: Regional Characteristics of Severe Summer Hailstorms in Illinois. Res. Rept. 14, Crop-Hail Insurance Actuarial Assoc., Chicago, 19 p.

Changnon, S. A., 1965: Prediction of Corn and Soybean Yields Using Weather Data. Res. Rept. 22, Crop-Hail Insurance Actuarial Assoc., Chicago, 30p.

Changnon, S. A., 1972: Examples of Economic Losses from Hail in the United States. J. Appl. Meteor., 11, pp 1128-1137.

Changnon, S. A., 1973a: Weather Modification in 1972 - Up or Down? Bulletin Amer. Meteor. Soc., 54, pp 63-66.

Changnon, S. A., 1973b: Study of Urban Effects on Precipitation and Severe Weather at St. Louis. Ann. Rept. 1972-73, NSF GI-33371, Illinois State Water Survey, Urbana, 34 p.

Changnon, S. A., 1975: A review of Methods to Evaluate Precipitation Modification. Proc. Int. Conf. on Wea. Mod., WMO, Geneva.

Dennis, A. S., and A. Koscielski, 1969: Results of a Randomized Cloud Seeding Experiment in South Dakota. J. Appl. Meteor., 8, pp 556-565.

Dennis, A. S., A. Koscielski, J. H. Hirsch, D. Cain, and P. L. Smith 1974: Cloud Catcher Report for 1972. Rept. 74-4, S. Dakota School of Mines and Technology, Rapid City, 121 p.

Grant, L. O., G. W. Brier, and P. W. Mielke, 1974: Cloud Seeding Effectiveness for Augmenting Precipitation from Continental Convective Clouds. Proc. Int. Trop. Meteor. Mtg., Amer. Meteor. Soc., Boston, 5 p.

Hosler, C. L., 1969: The Role of Weather Modification in Alleviation of Droughts. Earth and Mineral Sci., Vol. 38, Penn. State Univ., pp 53-57.

Huff, F. A., 1971: Evaluation of Precipitation Records in Weather Modification Experiments. Adv. in Geophysics, 15, pp 59-135.

Huff, F. A., and S, A, Changnon, 1972: Evaluation of Potential Effects of Weather Modification in Agriculture. J. Appl. Meteor., 11, pp 376-384.

Kasemir, H. W., 1975: Effect of Chaff Seeding on Lightning and Electric Fields. Proc. Int. Conf. on Wea. Mod., WMO, Geneva.

Miller, J. R., E. I. Boyd, and R. A. Schleusener, 1974: Hail Suppression Data From Western North Dakota, 1969-72. Preprints 4th Conf. on Wea. Mod., AMS, Boston, pp 139-142.

Morgan, G. M., 1973: A General Description of the Hail Problem on the Po Valley of Northern Italy. J. Appl. Meteor., 12, pp 338-353.

Simpson, J., 1973: Bayesian Statistics Applies to Florida Cumulus Modification Experiments. Preprints 3rd Conf. on Prob. and Stat. In Atmos. Sci., Amer. Meteor. Soc., Boston, pp 73-80.

Simpson, J., and W. L. Woodley, 1971: Seeding Cumulus in Florida: New 1970 Results. Science, 172, pp 117-126.

Simpson, J., and A. S. Dennis, 1972: Cumulus Clouds and Their Modification. NOAA Technical Memo. ERL OD-14, U.S. Department of Commerce, Boulder, Colorado, 148 p.

Thompson, L. M., 1965: Iowa Agriculture, World Food Needs and Educational Response. Center for Agricultural and Economic Development, Iowa State Univ., Ames, 15 p.

U. S. Department of Agriculture, 1955: Water, the Yearbook of Agriculture. U. S. Government Printing Office, 751 p.