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April 1973

USE OF METEOROLOGICAL SATELLITE OBSERVATIONS IN WEATHER MODIFICATION PROGRAMS

By: A. S. Dennis, P. L. Smith, Jr., and K. R. Biswas

Prepared for:

National Aeronautics and Space Administration
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Institute of Atmospheric Sciences

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ABSTRACT

This report summarizes investigations into the potential value of weather satellite data in field operations in weather modification. A comparison of the capabilities of present satellite sensors with the observational requirements for weather modification experiments tabulated in a previous report suggests that the role of satellites in such experiments will be limited.

Further examination shows that satellites could play a useful role in operational weather modification projects, particularly in the recognition of treatment opportunities. Satellite cloud photographs and infrared observations appear promising in the identification of treatment opportunities in seeding orographic cloud systems for increased snowpack, in seeding convective clouds for increased rainfall, in identifying hail threats, and in tracking and observing hurricanes as an aid to timing and location of seeding treatments. On the other hand, satellites would be of little or no value in the seeding of semi-orographic winter storms on the west coast of the United States, as this requires the identification of convective bands within the storms and these are usually obscured by overlying cirrus and cirrostratus clouds.

The potential value of satellite data in the treatment and evaluation phases of operational projects is not as great as in the recognition of treatment opportunity.

It is concluded that:

1) Satellite data should be made available in real time to one or more ongoing field projects as a means of establishing more closely the value of such data.

2) The advance in sensor technology that would be most useful to weather modification is improved capability for determining cloud top heights or temperatures.

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1. INTRODUCTION

This report is the fourth in a series concerned with the potential value of satellite technology in future weather modification programs.

The first report in the series (Anderson, 1969) summarized the meteorological observations then being acquired from satellites in terms of the variables being measured and the accuracy and resolution of the data collected. The second report (Biswas and Dennis, 1971) contained a survey of weather modification experiments and programs throughout the world from 1946 to 1970. On the basis of that survey, the meteorological observations likely to be required in future weather modification programs were set down. This tabulation was carried out without regard to whether any satellite instrumentation in existence or theoretically possible could, in fact, perform the necessary measurements. The third report in the series (Biswas, 1972) examined the potential value of cloud pictures obtained from both low-orbit and geosynchronous satellites in weather modification projects in the northern Great Plains region. That after-the-fact case study showed that visible and infrared satellite cloud imagery would be useful in conducting weather modification activities if the imagery were made available in real time.

This fourth and final report attempts to draw together the previous reports and points out where apparent matches exist between the meteorological observations required and the capabilities of satellite-borne sensors. Some recommendations are also made concerning the directions of future developments in satellite technology that would be most beneficial to weather modification programs.

2. DIRECT COMPARISON OF REQUIRED OBSERVATIONS AND SATELLITE CAPABILITIES

A comparison of the requirements specified by Biswas and Dennis (1971) for meteorological observations in weather modification projects with the capabilities of existing satellite instrumentation shows that the satellites are incapable of most of the detailed measurements required. This can be seen by examining Table 1, which is a composite of the several tables compiled by Biswas and Dennis (1971) showing their estimates of the observations required for various weather modification activities. Of all the variables listed in Table 1, cloud cover (type and amount) and cloud top height or temperature are the only two that present-day satellite sensors can observe with capabilities approaching those called for (Rao, 1970). Satellite cloud imagery in the visible and infrared gives data that can be used to estimate values for both of these variables. For example, spectral signature methods involving one solar reflectance and three thermal infrared channels were used to determine cloud types from Nimbus 3 Medium Resolution Infrared Radiometer (MRIR) data (Lo and Johnson, 1971). Radiometers working in the 11-micron window region, such as the Temperature Humidity Infrared Radiometer (THIR) carried on recent Nimbus satellites, can achieve a measurement accuracy of 1C or better for the cloud-top temperatures of water clouds, although the results are less satisfactory for ice clouds.

To achieve the repetition times called for in Table 1, the cloud observations (as well as the other ones listed) have to be made from geostationary satellites. A low-altitude polar-orbiting satellite provides observations for a given point on the earth at roughly 12-hour intervals. Shorter repetition times are possible with a system of multiple polar-orbiting satellites, but a practical system of this type has yet to be developed. Unfortunately, not all of the existing or proposed satellite remote sensing techniques can be used with geostationary satellites. The decreases in spatial resolution and radiometric sensitivity render some techniques that are useful with low-altitude satellites impractical from geostationary orbits. For instance, the methods used to establish cloud top heights from polar-orbiting satellite observations have yet to be proven when the imagery is obtained from geostationary orbits.

Table 1 calls for measurement of temperature with an accuracy of ± 0.5C and a vertical resolution of 50 to 100 m. Comparison with performance data tabulated by Anderson (1969) shows that making temperature measurements with the required accuracy and vertical resolution from a satellite was not possible at that time. Consideration of more recent instrument developments does not remove the difficulty (Smith _et al._, 1972). The present practice in temperature sounding from

TABLE 1: PRINCIPAL MEASUREMENTS NEEDED IN WEATHER MODIFICATION PROGRAMS AND THEIR SPREAD IN REQUIREMENTS

Measurements or Observations	Accuracy	Repetition Time (hr)	Vertical Resolution (meters)	Horizontal Spacing (km)
1. Vertical Soundings				
Temperature	± 0.5C	0.2-6	50-100	10-50
Pressure	± 0.5 mb	3	100-1000	10-50
Precipitable water or	± 1 mm	3-6	1000	10-25
humidity lapse rate	± 0.5C	3-6	100	10-25
2. Wind Measurements				
Wind aloft				
a. Direction	± 10°	0.1-3	50-1000	1-15
b. Speed	± 0.03-0.5 m/sec	0.1-3	50-1000	1-25
Low level upcurrent	± 0.1 m/sec	7	100	15
3. Cloud Structure and Composition				
Cloud type, amount and detailed structure	± 0.05 of sky	1	100 km^2 (Hor. resolution)	10-continuous
Height of base and top of cloud/fog	± 50-500 m	0.2-3	---	1-50
Cloud/fog liquid water content	± 0.01-0.1 g/m^3	0.1-3	100-500	0.1-25
Cloud particle size (Modal diameter and spread)	± 1 micron	0.1-1	100	1-15
Cloud phase	± 0.1	0.05	100	0.1
Cloud updraft speed	± 1 m/sec	0.2-1	100-1000	As required

4. Precipitation Measurements				
Rain or snow				
a. Type	---	0.2	---	1-10
b. Rate	25%-Factor 2	0.2-0.25	---	1-10
c. Amount	5%-Factor 1.5	1-24	---	1-100
Hail				
a. Size	0.5 mm	---	---	1
b. Energy	± 1 ft-lb/ft^2	---	---	1
5. Aerosol Measurements				
a. Giant condensation nuclei	± 0.01/liter	6	1000	30
b. Freezing nuclei	± 1/liter-Factor 2	1-6	500-1000	10-30
c. Cloud nuclei	10%	6	1000	30
6. Other Measurements				
Visibility	± 20%	0.2	---	1
Flux of heat and moisture from ground or sea	± 0.1 cal cm^{-2} min^{-1}	3	---	50-100
Electrical activity				
a. Lightning strokes b. Sferics frequency and strength c. Space charge d. Electric field e. Field strength change	± 10%	Continuous	---	15

satellites is to determine temperature profiles through inversion of observations of the radiance in various infrared channels. The inherent vertical resolution of these profiles in the lower troposphere is no better than about 4 km, and reducing the temperature errors to even 1C is difficult. The latest developments offer little hope for significantly increasing the number of tropospheric levels. Improvement to the degree required to provide temperature observations with 100 m vertical resolution appears to be out of the question both now and for the foreseeable future (e.g., Weinreb and Crosby, 1972).

Passive vertical sounding techniques involving the use of radiometry in the infrared region to determine profiles of temperature and other variables generally have vertical resolution much poorer that that called for in Table 1. The planned use of similar radiometric techniques in the microwave region does not offer much prospect of improving the vertical resolution. Moreover, those variables that can be studied with multi-spectral microwave radiometers, such as cloud liquid water content or precipitation, cannot be observed with the necessary horizontal resolution, especially from geostationary orbits. In fact some of the microwave techniques require viewing at substantial angles (such as 50°) off the nadir; such techniques cannot be used at all from geostationary orbits. The microwave scanners are large, heavy, and require substantial amounts of power for operation; their actual feasibility for routine use in orbit remains to be demonstrated.

Similar difficulties arise in connection with most of the observations specified in Table 1, including vertical distributions of pressure, water vapor, and wind direction and speed. Furthermore, Table 1 includes many variables which cannot be measured at all from satellites at this time. These include all the precipitation data and the concentrations of giant condensation nuclei, freezing nuclei, and other aerosol particles. Conceivably, limited information on some aerosol particles will some day be derived by lidar or other techniques, but those special aerosol particles (ice nuclei) which play key roles in cloud glaciation are virtually certain to remain indistinguishable from ordinary aerosol particles as far as remote sensing from satellite platforms is concerned.

Some experiments involving the use of satellite observations to determine cloud structure and composition are planned for the post-Nimbus era (1976 and beyond). These experiments will involve a scanning multi-spectral reflectometer working in the solar infrared region (roughly 0.75 to 2.13 micron wavelength) and a scanning multi-spectral microwave radiometer operating in the 0.8 to 6.0 cm wavelength region. The data will be used to derive information about such variables as water vapor profiles; the liquid water content, droplet sizes, and water phase (liquid or solid) in clouds; and precipitation distributions. These experiments are likely to yield some data that would be useful in weather modification activities, but the exact sensor capabilities are as yet unknown so it is difficult to determine whether they will meet the requirements listed in Table 1. At present, most of the projected capabilities seem to fall short of those required to support weather modification activities. Moreover, not all of the proposed experimental techniques are capable of being used from geosynchronous orbits. As is often the case, however, weather modifiers may learn to make effective use of data that is less than ideal.

One category of satellite observational capability not readily brought to mind by examining Table 1 is the ability to collect data from fixed or moving platforms on the surface of the earth or in the atmosphere, and also to determine the location of the moving platforms. This data collection capability could be used to acquire temperature, wind, humidity, precipitation, and other meteorological data from the platforms. Such data have a wide variety of applications in weather modification as well as elsewhere. The capabilities of such data collection systems are being explored with experimental systems on ERTS-1, GOES, and other satellites. Present indications are that while the systems are technologically feasible, the economics are in doubt if any sizable number of platforms is needed. However, further developments in system technology may lead to reduced costs that will make such systems more attractive in the future.

The foregoing discussion may seem to downgrade the role of satellites in weather modification programs. Essentially similar conclusions were reached in an unpublished study by a Meteorology Program Working Group at Goddard Space Flight Center ("An Assessment of the Capability of Meteorological Satellites to Provide Observations for Weather Modification," March 1, 1972). However, it should be noted that many of the requirements posed in Table 1 cannot be met by <u>any</u> existing data collection system. To quote from Biswas and Dennis (1971):

> ". . . weather modification pioneers have visualized their needs being met by 'more of the same', e.g., by additional radiosonde stations. It appears to us that the frequent observations at close spacings required for experiments on convective clouds in particular must be met by new approaches, if costs are to be kept within reason. In fact, some of the requirements pose almost insuperable physical problems if solutions are sought by conventional means; for example, how many sampling aircraft can fly through a cloud without altering its characteristics? However, calls for radiosonde stations at spacings of 20 to 50 km will vanish if lidar probes provide continuous monitoring of the temperature, humidity, and wind fields in three dimensions, and remote sensing may also permit experimenters to keep their test clouds intact."

Substantial progress has been made in weather modification technology over the past 25 years despite the lack of ideal data collection networks. The inability of satellite instrumentation to fulfill all the requirements that can be listed is not grounds for dismissing it out of hand; the crucial question is, "Can the addition of satellite observations upgrade the existing capability?" Although there is a tremendous gap between what satellite instrumentation can do and what weather modification practitioners would like to have it do, we shall see that even the existing satellite instrumentation might make a significant contribution in weather modification programs.

3. RECOGNITION OF SEEDING OPPORTUNITIES

3.1 Cloud Seeding Windows

Many of the requirements listed by Biswas and Dennis (1971) were derived assuming a need to evaluate weather modification experiments. Evaluation imposes stringent requirements in specifying the conditions both before and after a cloud seeding experiment so that differences from the normal evolution of events can be ascribed to the seeding treatment. The requirements in operational situations are less onerous.

Now that many hundreds of cloud seeding experiments have been carried out in various parts of the world, a consensus is slowly developing concerning conditions under which successful weather modification operations can be carried out for various purposes. These conditions have been called "windows", a good term in view of the rather restricted range of conditions under which various desired effects can be demonstrated.

The seeding windows turn out in some cases to be simply defined, so that satellite data could make a significant contribution to recognition of seeding opportunities. For example, in seeding orographic clouds for increases in snowpack, it has been shown in certain areas that significant increases occur if the cloud top temperature is in the range from -12 to -23C but not otherwise. In the seeding of semi-orographic storms in the coastal mountain ranges of California, the important increases in rainfall are obtained from the convective bands embedded within such storms. In seeding for rain increase in shower situations in the northern plains, the increases are apparently limited to clouds with depths between 10,000 and 30,000 ft, which in summer usually corresponds to clouds with tops from 20,000 to 40,000 ft MSL and cloud top temperatures between -10 and -40C. On the other hand, hail suppression operations are usually not needed until cloud top temperatures drop below -30C. In each of the examples where the "windows" can be identified in terms of cloud top temperatures, it is conceivable that satellite sensors alone could provide the information needed to recognize when conditions are within the appropriate "window".

A short discussion of each of the situations just mentioned will now be given.

3.2 Seeding Orographic Clouds for Increased Snowpack

It was recognized as early as 1949 that seeding orographic clouds with silver iodide to increase snowpack was one of the most promising areas for weather modification experimentation.* The final report of the Advisory Committee on Weather Control, which was issued in 1957, included evidence that increases in snowpack and rainfall amounting to 9 to 17% of the natural precipitation were being obtained by commercial cloud seeders in mountainous regions of the western United States.

The discovery of the important window for silver iodide seeding of purely orographic clouds sprang from a long series of randomized experiments carried out near Climax in the Rocky Mountains by Colorado State University using ground based silver iodide generators. Originally defined in terms of 500-mb temperature, the window now seems to be actually related to cloud top temperature. Increases in snowpack occur with cloud top temperatures in the range from -12 to -23C but not otherwise. There is some evidence that silver iodide seeding when cloud top temperatures are below -23C can lead to decreases in snowfall 10 or 15 miles downwind of the generators. However, it has been suggested that increases might occur further downwind after the ice crystals produced by seeding have diffused sufficiently to reach fresh supplies of supercooled water and resume their growth.

Experiments in the Park Range in Colorado and in the mountains of New Mexico sponsored by the U. S. Bureau of Reclamation under Project Skywater tend to confirm the Climax results. The 500-mb temperature window may vary somewhat from one geographic location to another (e.g., Keyes et al., 1972), but the variation in cloud top temperature limits should be small, as the window appears related to the ice nucleating characteristics of silver iodide as opposed to natural ice nuclei. Results from New Mexico State University, so far unpublished, indicate that the snowpack yield on a small watershed can sometimes be doubled for storms where the cloud top temperature falls in the -10 to -20C range.

The ability of satellite infrared radiometers to measure cloud top temperatures to within ± 1C is obviously adequate to determine whether or not a given orographic cloud system falls within the cloud seeding window for increased snowpack. Furthermore, with some radiometers having a horizontal resolution of only a few kilometers, it appears quite feasible to use the data to determine which parts of a watershed have clouds with top temperatures in the seeding window. For example, an operational program covering those parts of western Colorado draining into the Colorado River could use the satellite infrared data to determine which particular tributary watersheds were overlain by suitable target clouds.

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*References to the original papers and reports listed by Biswas and Dennis (1971) will not be repeated here.

Satellite data have not yet been made available to the orographic seeding experiments at Climax. Colorado State University is in the process of acquiring a receiver for geostationary satellite data, but the intention is to use the data for after-the-fact analysis rather than for forecasting or as an aid to seeding decisions.* It appears to us that it would be worthwhile to try using the satellite data in real time to guide seeding decisions in the Climax experiments.

While information comparable to that provided by the satellites could be inferred from frequent, closely spaced radiosonde observations or from aircraft probes, both of these methods are inconvenient (and the latter even dangerous in mountainous terrain) compared to the use of meteorological satellites. It appears that orographic seeding is one situation where geostationary satellites offer a definite advantage over any other method of performing the same task.

3.3 Detection of Convective Bands in West Coast Storms

The winter storms in the coastal ranges of the western United States were characterized as semi-orographic in the Advisory Committee report because the coastal ranges do not extend upward to the regions colder than -5C where silver iodide becomes effective. Therefore, the silver iodide seeding agent cannot be carried upward to where it becomes effective by purely orographic means, but must be carried by diffusion or convective currents into the supercooled cloud regions.

The term semi-orographic is appropriate in another sense, as study of these storms has shown that convective activity, which is often organized in bands, plays a key role as a precipitation mechanism within them. Viewed in this sense, precipitation in the western foothills of the Sierra Nevada and Cascade ranges is also of a semi-orographic nature.

Studies in Santa Barbara and Santa Clara counties in California have indicated that the convective bands produce a substantial fraction of the total rainfall associated with the storms and also offer the greatest opportunity for rainfall increases through silver iodide seeding. Therefore, the optimum conduct of a seeding project to increase rainfall along the coastal ranges of California, and probably of Oregon and Washington as well, requires the identification of the convective bands as they move in from the Pacific Ocean and the deployment of ground based or airborne seeding equipment to treat the bands as they progress inland.

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*Private communication from Professor L. O. Grant.

The convective bands in west coast storms are characterized by cumuliform clouds, which have higher liquid water contents and are more compact than the stratiform clouds in the intervening spaces. However, the convective clouds are usually topped at 20,000 to 25,000 ft MSL and are often overlain by decks of cirrus and cirrostratus clouds which tend to obscure them.

Mr. Keith Brown of North American Weather Consultants, Goleta, California has provided us with ATS-1 satellite pictures for three storms in the fall of 1971. The pictures show the frontal cloud systems but not the embedded convective bands. As an example, four bands were identified from radar and telemetered rain gage data during the storm of November 11-12, 1971, but these cannot be distinguished on the ATS-1 picture for 2149Z on 11 November (Fig. 1). Mr. Brown has stated in a private conversation that North American Weather Consultants have not used satellite photographs as operational tools in their work in Santa Barbara County and, for the reasons noted above, see little incentive to do so.

As implied above, the convective bands are usually identifiable with ground based radar. Successful tracking of the bands through mountainous terrain with conventional weather radar sets is sometimes difficult because of ground clutter. Satellite photographs might be able to identify convective bands over the mountains where ground based radar could not, but these situations are expected to be rare.

Satellite-borne radar or microwave radiometry may offer possible ways to identify the bands, but the sensors are not yet available for the purpose and they are not likely to be usable from geostationary orbits.

For the time being at least, we conclude that satellite data will be of very limited value in semi-orographic seeding projects.

3.4 Rainfall Increases from Convective Showers

The first randomized experiments to test the possibility of increasing rainfall from convective clouds over the continental United States by silver iodide seeding were inconclusive. These experiments, which included the well known Whitetop Experiment in Missouri and an experiment by the University of Arizona, were for a time widely accepted as evidence that seeding convective clouds for additional rainfall was not a productive effort.

The success of statisticians analyzing the Climax experiments with data stratification suggested a similar approach in experiments on convective clouds. New experiments were started in Florida, South Dakota, near Flagstaff, Arizona and elsewhere, in which increased attention was

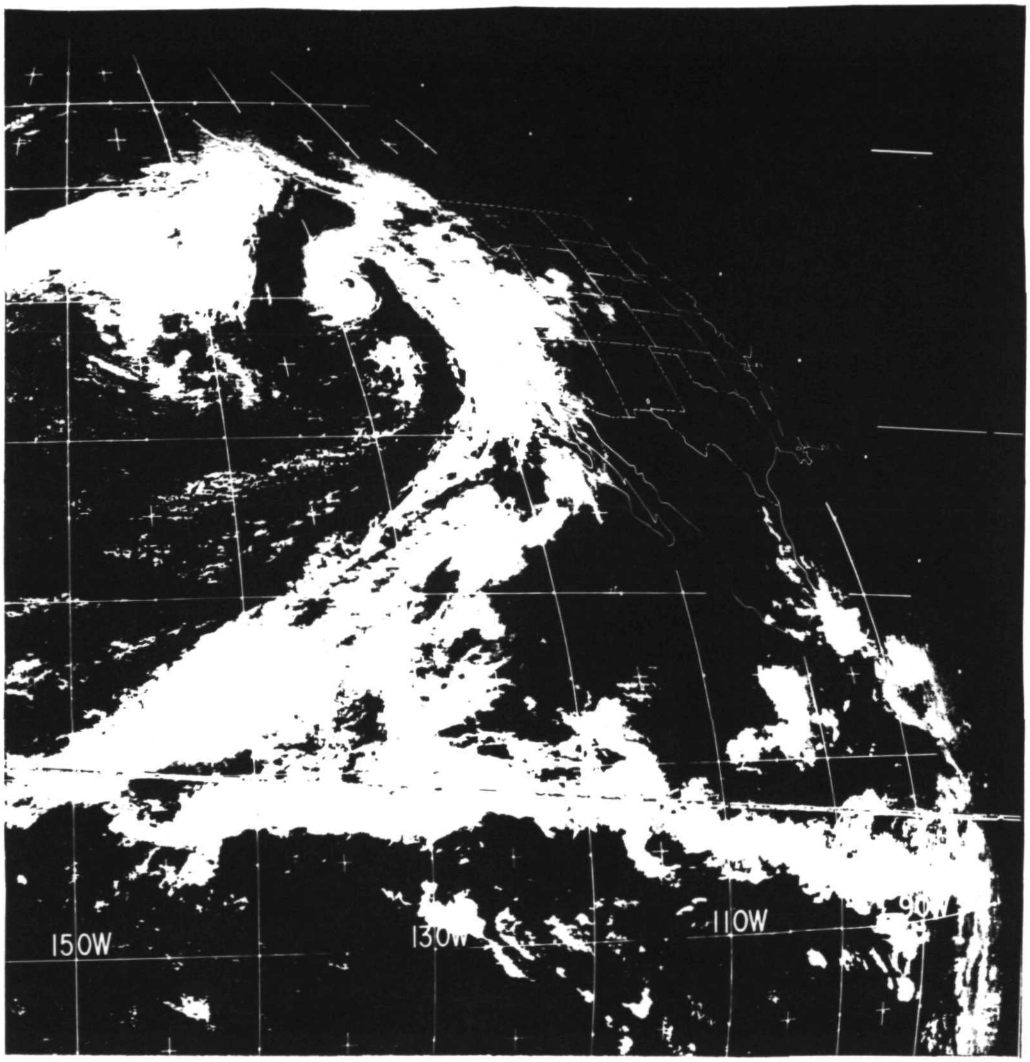

Fig. 1. Part of ATS-1 picture for 2149Z, 11 November 1971 showing western United States. Mesoscale analysis revealed four convective bands within the frontal cloud system covering the central California coast.

paid to such factors as cloud temperatures, liquid water contents, and the degree of stability or instability of the air masses in which the convective clouds were occurring. In addition, new analyses were performed in which data stratification was applied to the data samples collected on the Whitetop and University of Arizona projects.

The new experiments are not finished, and much remains to be done in working out basic relationships so that results obtained in various parts of the country can be shown to be special cases of general rules. However, the general outlines of the windows for convective clouds are becoming apparent (Simpson and Dennis, 1972), and are briefly noted in the following paragraphs.

Seeding with hygroscopic materials such as common salt is effective in increasing precipitation from convective clouds in the northern plains region with depths ranging from 10,000 to 30,000 ft. As convective cloud bases in the High Plains are often around 10,000 ft MSL, these depths correspond to convective clouds with tops from 20,000 to 40,000 ft MSL. Presumably, in regions where cloud liquid water contents tend to be higher, in southern Texas for example, the limits on cloud thickness for successful hygroscopic seeding would be lowered somewhat. Data to determine the limits of the salt seeding window in areas other than the northern Great Plains are not available as yet.

The silver iodide seeding window for rain increases in convective clouds of the northern plains happens to coincide closely with the salt seeding window. At the risk of oversimplification, one can say that convective clouds of the northern plains become deep enough for hygroscopic seeding agents to work at about the same time the cloud top temperature becomes cold enough for silver iodide seeding to work. The limits on cloud tops of about 20,000 to 40,000 ft MSL can be translated into cloud top temperatures of -10 to -40C to define the silver iodide window. Data from Florida and California suggest that these temperature limits on silver iodide seeding are appropriate in other areas, but some adjustments may be necessary.

Biswas (1972) demonstrated that towering convective clouds can be identified on the basis of their appearance in satellite photographs. However, better results could be achieved with infrared temperature determinations. The limiting factor here would be whether or not the towering cumulus clouds are big enough to register on the infrared radiometers during daylight hours when most convective activity takes place. The seeding targets being sought are from 3 to 7 km deep. As the horizontal dimensions of convective clouds are comparable to their depth, horizontal resolution of the order of 5 km would be required to avoid determining a mean IR temperature representing an average over the convective clouds and the ground visible between them. Comparison of this requirement with the capabilities of present and forthcoming satellite-borne radiometers indicates that the required resolution is now available from low-altitude satellites and may soon be achieved from geosynchronous satellites as well. Therefore the satellite data, if available in real time, would not only identify whether or not suitable convective clouds for rain increase seeding existed over a large region such as the northern Great Plains but could even locate within that area the groupings of clouds to which seeding aircraft could most profitably be directed.

It does not appear that satellite data could locate areas of convective activity before the actual cloud development. Development of convective activity requires an unstable lapse rate from near the surface up to 25,000 ft MSL or so and moisture in the lower layers. The temperature profile cannot be determined with the required vertical resolution, nor can the moisture profile near the ground. The IR channels which respond to water vapor respond principally to water vapor in the upper troposphere, say around 500-300 mb. This region is not the <u>source</u> of water vapor for convective storms but rather their sink for water not precipitated to the ground.

Silver iodide seeding of convective clouds can, in certain lapse rate conditions, lead to increases in cloud size and hence to large percentage increases in rainfall. This approach (dynamic seeding) has been emphasized in experiments in Florida and at Flagstaff, Arizona. Satellite instrumentation cannot observe temperature profiles with sufficient vertical resolution to identify the necessary conditions. If dynamic effects were sought, one would therefore have to supplement satellite data with conventional radiosonde or aircraft information.

3.5 Hail Suppression

Biswas (1972) noted that certain large storms of 1971 in North Dakota at which hail suppression efforts were directed, mainly on the basis of radar observations, were clearly identifiable as individual entities on satellite cloud photographs. A good example is shown in Fig. 2. The size and brightness of these clouds and the intervening clear spaces make them stand out, a fact well documented in previous studies unrelated to weather modification activities. Substantial skill has been demonstrated using geostationary satellite imagery in conjunction with weather radar observations to identify and forecast outbreaks of severe weather (see, for example, Purdom, 1971). Other studies have shown correlations between cloud top heights or temperatures and the severity of hail at the earth's surface; therefore, it appears that cloud top temperature determinations by satellite-borne infrared radiometers would also be valuable in detecting hail threats. As a general rule, hail suppression activities would be called for whenever the cloud top temperature was colder than perhaps -30C and massive clouds appeared in the pictures. Cloud top

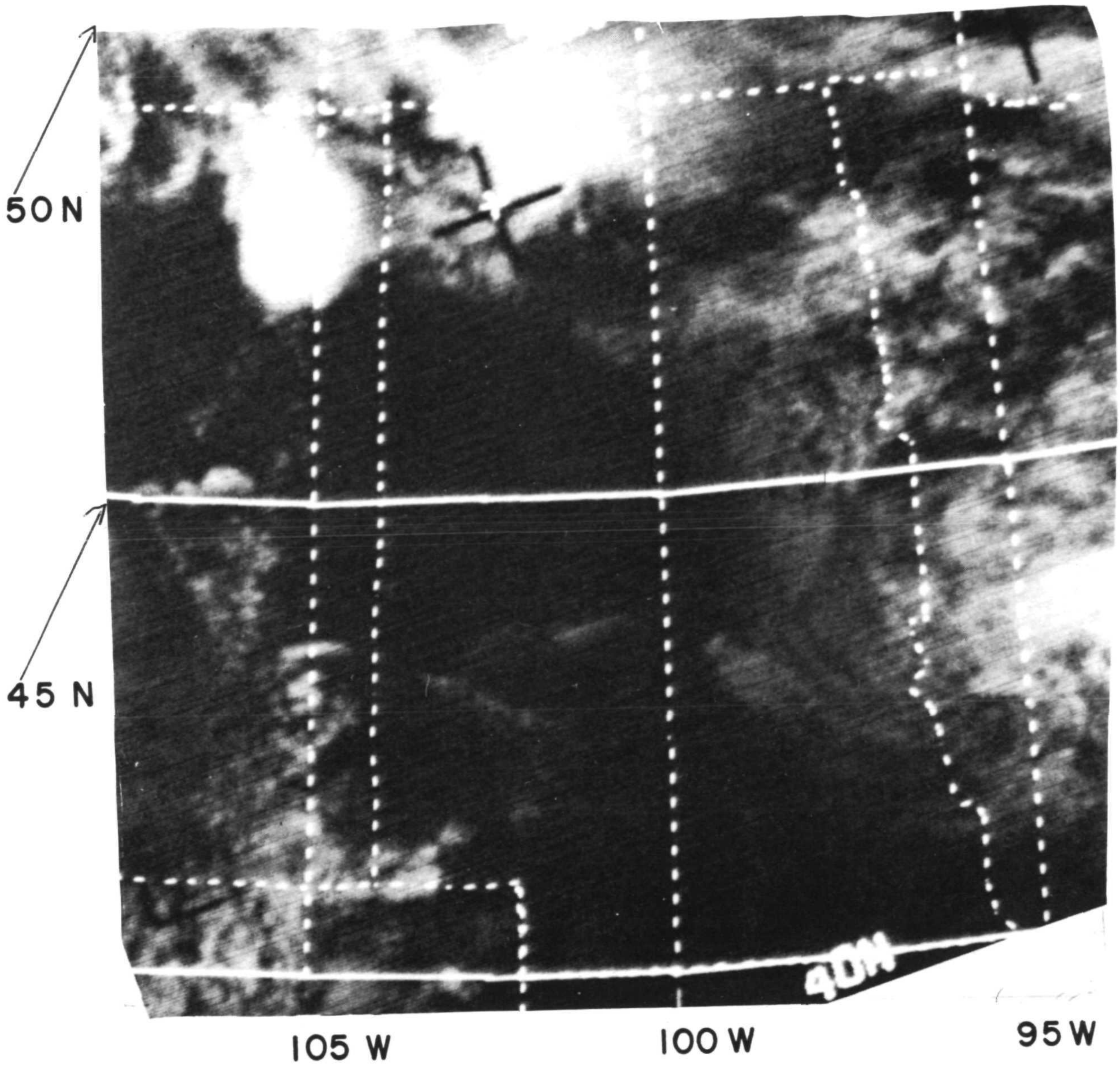

Fig. 2. NOAA-1 picture of northern Great Plains region at 1440 MDT on 10 July 1971. A severe convective storm appears in eastern Montana near 48N, 105W. Storms moving southeastward from eastern Montana caused severe hail damage during the evening in southwestern North Dakota and north-central South Dakota [after Biswas (1972)].

temperatures below -30C in the absence of bright, sharp cloud masses would be attributed to overlying cirrus or cirrostratus decks and not interpreted as an indicator of a hailstorm.

The severity of hail at the ground in Great Plains thunderstorms is positively correlated with the amount of air passing upward in the form of convective currents. Moderately severe hailstorms process something over 10^8 kg of air and 10^6 kg of water vapor per second. Severe hailstorms process about 10^9 kg/sec of air or about 10^7 kg/sec water vapor. A recent study at the University of Wisconsin (Auvine and Anderson, 1972) has shown that the volume flux of a storm can be estimated from the spread of the cumulonimbus anvil cloud as viewed from a geosynchronous satellite. This offers yet another possible method of alerting weather modification crews to hail threats, which is usually done on the basis of weather radar observations.

3.6 Hurricane Modification

The few actual experiments with tropical hurricanes conducted to date have yielded tantalizing evidence suggesting that wind speeds in hurricanes can sometimes be decreased by seeding with silver iodide in selected portions of the eyewall clouds. Computer models have suggested that seeding in the spiral rainband clouds would also affect the storm dynamics.

One difficulty in hurricane modification experiments is that few countries are willing to accept the risks involved in hurricane modification experiments near their shores. Project Stormfury has been conducted over the Caribbean Sea and tropical Atlantic at points well away from the mainlands of North and South America and inhabited islands. About 1970 it was suggested that the project should move to the Pacific Ocean because this would provide a greater number of seeding opportunities well away from land. The difficulties of mounting extensive observational programs in mid-ocean suggest that all possible methods of data collection, including satellite observations, should be fully explored.

The ability of weather satellites to detect and track hurricanes has already been well established, as has their ability to record the locations of the eyewall clouds and the rainband clouds (Fig. 3). As the brightness of tropical clouds as seen in satellite photographs has been shown to be positively correlated with rainfall rates (e.g., Woodley and Sancho, 1971), some information about storm dynamics can also be inferred from the photographs. Therefore satellite data should be helpful in deciding when seeding attempts should be made for hurricane modification and in determining the coordinates of those parts of the eyewall or rainband clouds to be treated.

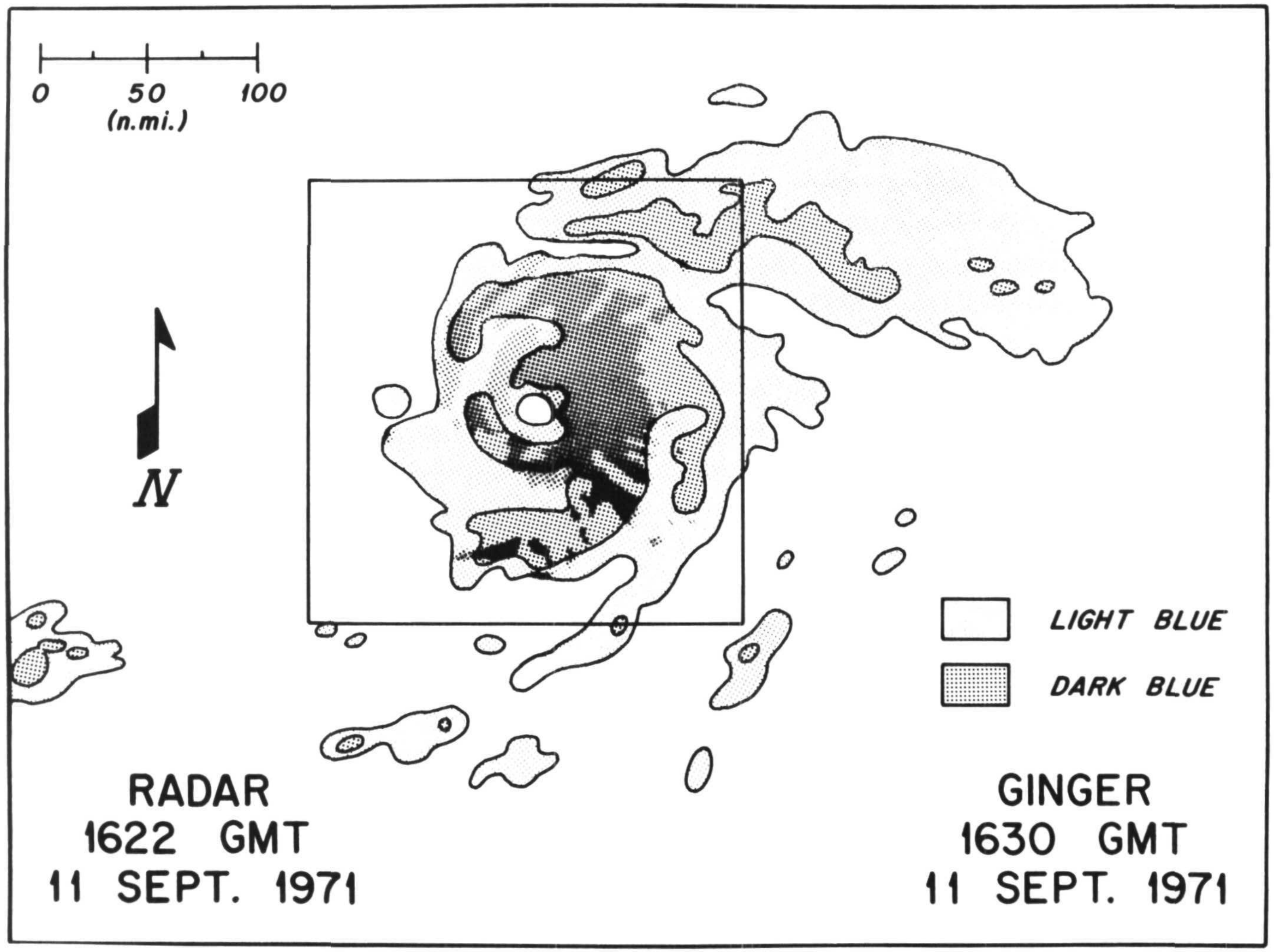

Fig. 3. Analysis of Hurricane Ginger at 1630Z on 11 September 1971 comparing rain areas as viewed by radar (solid shading) with cloud areas seen from satellite. "Dark blue" shading corresponds to bright cloud images. Hurricane eye, eyewall cloud, and spiral rainband clouds can be distinguished.

4. APPLICATION OF TREATMENT AND EVALUATION OF RESULTS

In addition to the recognition of seeding opportunities, any weather modification program involves some kind of treatment phase followed by an evaluation of the results obtained. Although we believe that the most fruitful applications of satellite technology will come in the recognition phase, it is worth considering some possible applications in the treatment and evaluation phases.

4.1 Treatment Phase

In general, application of a weather modification treatment in a given situation requires selecting the technique or seeding agent to be used and then directing its application to the appropriate part of the weather system. For example, selecting the seeding agent may involve a choice between a hygroscopic material such as common salt and an ice nucleating substance such as silver iodide. The basis of the choice may involve such factors as the intended objective (for example, rain stimulation versus hail suppression) and whether or not the clouds to be treated reach temperatures cold enough for ice nucleating materials to become effective.

Satellite observations of cloud top heights and/or temperatures would be useful in assessing the latter factor. As a practical matter, however, the seeding agent must usually be selected well in advance of the actual treatment because of logistic considerations. Satellite observations of the cloud top heights and temperatures are only possible at the time of occurrence. Forecasts of these variables adequate for the selection of seeding agents can usually be made from conventional radiosonde data with the aid of numerical cloud models. This approach has been followed with success in this Institute's Project Cloud Catcher, NOAA's Florida cumulus project, and elsewhere. Satellite observations may provide part of the data base from which these forecasts are developed, but the resolution available in vertical soundings from satellites does not permit the use of such data directly.

In applying the treatment, two kinds of decisions have to be made. One is where and when to introduce the seeding agent into the weather system. In making this kind of decision, satellite observations of cloud developments would be very useful if they were available to the project meteorologist in real time. For the observations to be timely, they would have to come from geosynchronous satellites capable of providing continuous coverage of the area of interest. The ability to follow the approach of weather systems and note when one storm begins to decay or another to intensify would be a valuable aid in directing the seeding activities. Similar information is obtained from weather radar, but satellites have the advantages of being able to observe cloud developments prior to the formation of precipitation and to cover a much broader area.

The second kind of decision made in applying seeding treatments involves the amount of seeding material used and the rate at which it is dispensed. Such decisions are now made on a rather crude basis, but improving that basis would require more information about the concentrations of ice and condensation nuclei and cloud droplets and the ratio of ice to water particles present in the cloud. Thus, the necessary observations involve detailed measurements of the particulate makeup of the cloud. Neither ground-based nor aircraft observations of this type are now available in adequate form, but satellite techniques for studying cloud composition and discriminating between water and ice particles in cloud systems are only in the primitive stages of development at present. There appears to be little prospect that satellite technology can provide significant improvement in this situation in the foreseeable future, although it may eventually become possible to measure the concentration of ice crystals in the upper parts of the cloud systems with sufficient sensitivity to deduce whether the rate of application of ice nucleating agents requires adjustment.

4.2 Evaluation Phase

Turning our attention to the question of evaluating the results of weather modification activities, we may note that two general classes of observations are needed. The first class includes observations of the quantity to be modified, which is usually a precipitation variable (rainfall, hailfall, snowpack). However, some weather modification activities involve other variables such as visibility (in fog dispersal work) or wind velocity (in hurricane abatement). No capability exists to measure precipitation accumulations from satellites except in a very rough way (for example, the extent of snow cover areas). Recent work on the development of statistical techniques for estimating rainfall rates from satellite cloud pictures does show promise (Woodley and Sancho, 1971), and microwave radiometry can give some indications of soil moisture conditions. However, it appears unlikely that any such techniques can be developed in the near future which will be adequate for discerning the small differences in precipitation (sometimes 10% or less) that can be significant in weather modification.

Observations from a geosynchronous satellite of the spread of the cumulonimbus anvil of a severe storm could be compared with observations of hail on the ground, obtained by ground instrumentation networks or from aircraft carrying infrared sensors across the hailswath region, to provide a method of evaluation of hail suppression efforts. This possibility is being considered in connection with the National Hail Research Experiment, which is in progress in northeastern Colorado.

Satellite technology offers little potential assistance in evaluating attempts to modify other variables. For instance, even if visibility conditions could be observed from satellites, fog clearing is a local activity and such observations can more conveniently be made at the target location.

One place where satellite observations may turn out to be very useful in evaluation is in connection with hurricanes. The requirement to work over the oceans makes it difficult to collect conventional weather data, as was noted in Section 3.6. The usefulness of satellite observations may well be greater in the absence of such other data. Moreover, one major objective of hurricane modification experiments is reducing the wind velocities in the most intense part of the storm. There is reason to hope that estimates of the wind velocities useful in evaluating any such reduction can be obtained from geostationary satellite observations of the hurricane clouds.

The second class of observations needed for evaluation include those that can be used to stratify the data. The stratification can be based on such variables as cloud top temperatures or maximum updraft speeds, as was discussed in Section 3. In most cases adequate information for stratification purposes can be obtained from conventional data sources. The stratification can be done well after the actual modification, so there is plenty of time to collect all the necessary data. Satellite inputs may be valuable in establishing the data base but their direct effect on the stratification process would seem to be limited. Here again, hurricane modification work over the oceans may represent a significant exception.

The data collection capabilities being developed for some satellite systems may turn out to be useful in evaluating weather modification activities if the system costs can be reduced far enough. In many weather modification programs the collection of precipitation and other data from extensive surface networks requires a substantial expenditure of time and funds. Satellite data collection systems could in many cases acquire the necessary data more effectively than traditional methods. However, the costs of the systems and especially of the units needed to relay the data to the satellites will have to be substantially reduced before such data collection systems can be widely used.

Some variables may be observable by satellite that cannot be measured conveniently in any other way. For example, it may be possible in some cases to determine the area covered by rain on a given day from satellite observations. The value of any such "unconventional" observations in the evaluation of weather modification activities is speculative at best. Future research may reveal some use for such observations but at present there is no firm basis for assigning any value to them in connection with the evaluation of weather modification activities.

5. RECOMMENDATIONS AND FUTURE PROSPECTS

Our attempts to determine the value of meteorological satellite data in weather modification programs by comparing available observational capabilities against the tables of data requirements have shown that in most cases the satellites cannot by themselves fulfill the requirements. However, we have been able to identify a number of situations in which satellite data would be of value, especially in the recognition of opportunities for treatment. In some cases, for example in seeding to increase snowpack over the Rocky Mountains during winter storms, the satellites offer much more complete data than can be obtained in any other way without excessive cost. In other cases, the satellite data merely complement the data available from other sources.

The meteorological sensors used on satellites can be classified into five general categories:

(a) Framing devices, such as TV cameras;
(b) Low resolution non-scanning radiometers;
(c) Scanning multi-spectral radiometers;
(d) Radiometers used for vertical atmospheric sounding; and
(e) Data collection and platform locating systems.

Of these five categories, the first and third seem to offer the most promise in connection with weather modification activities, with the scanning radiometers likely to assume a dominant role in the future. Information from framing devices or scanning radiometers would have many useful applications in weather modification, especially if it could be made available in real time to aid in the recognition of seeding opportunities and the direction of the seeding activities. The horizontal resolution of the non-scanning radiometers and the vertical resolution of the atmospheric sounding techniques are generally inadequate to meet the data requirements of weather modification activities. The satellite data collection systems may ultimately prove to be useful, but at present their cost is prohibitive for most applications in weather modification.

The primary thrust of meteorological satellite programs in the past has been toward providing observations that can be used to formulate the initial conditions needed in numerical weather prediction models. A few data products such as those provided by the APT system have been furnished to help meet the needs of other users. The value of satellite data in sophisticated meteorological experiments will be evaluated more fully by virtue of its inclusion in the GARP Atlantic Tropical Experiment (GATE). However, it is our opinion that from the standpoint of weather modification more rapid progress would be made if satellite pictures or data were introduced in real time into some ongoing cloud seeding programs. We therefore recommend that a coordinated experiment be undertaken in which data from a geosynchronous satellite are made available in real time to a meteorologist directing some existing, well designed cloud seeding project. Only from this kind of first-hand experience will it be possible to evaluate with confidence the ability of satellite observations to contribute to weather modification programs.

In deciding what further developments in satellite technology would be of greatest benefit to weather modification programs, it is helpful to consider three possible directions in which satellite technology might evolve; they are:

(a) More accurate observations. Continued evolution of sensor technology and the associated data processing techniques can be expected to bring about gradual improvements in the accuracy of satellite observations of meteorological variables such as temperatures or wind velocities. However, dramatic step increments in accuracy seem for the most part unlikely. The greatest benefit to weather modification would accrue from improved accuracy in the measurements of cloud top heights and/or temperatures.

(b) Observations with finer spatial resolution. Improvements in sensor technology will likely result in some significant improvements in the horizontal resolution of satellite observations, but fundamental limitations weigh strongly against dramatic improvements in the vertical resolution. Unfortunately most of the requirements of observations for weather modification seem to call for improvement in the vertical resolution as the most essential step.

(c) More timely observations. Acquiring the satellite observations on a timely basis and making them available quickly (in a matter of minutes) to the user is a goal within the grasp of present-day satellite technology. Making such observations available to weather modification programs requires an operational geosynchronous satellite system with direct communication links (perhaps similar to the APT system) to user ground stations. Even if the data comprise only visible and infrared observations of cloud patterns, the impact of such data inputs on weather modification activities would be tremendous.

Operational geosynchronous satellites with direct data links are well within the reach of present-day technology and are in the planning and development stages. The greatest benefit that the satellite program could provide to weather modification would accrue from continuation of this development work and early implementation of an operational geosynchronous meteorological satellite capability. We emphasize again the need for the real time communication link: The principal uses of the observations would be in the opportunity recognition and treatment phases of weather modification activities, and this requires real time data.

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