

Meteorological Satellites in Support of Weather Modification

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Abstract

During the past several years, many weather modification programs have been incorporating meteorological satellite data into both the operations and the analysis phase of these projects. This has occurred because of the advancement of the satellite as a mesoscale measurement platform, both temporally and spatially, and as the availability of high quality data has increased. This paper surveys the applications of meteorological satellite data to both summer and winter weather modification programs. A description of the types of observations needed by the programs is given, and an assessment of how accurately satellites can determine these necessary parameters is made.

1. Introduction

The advancement in meteorological satellite technology has been rapid over the past decade. In the 1960s we saw the development of sun synchronous polar orbiter satellites with both visible and IR wavelength sensors that could monitor "weather" twice daily. These were very useful in monitoring synoptic scale disturbances but lacked the temporal frequency necessary to monitor short-term weather features. In 1966 the first geosynchronous meteorological satellite was launched; it provided visible imagery (4 km resolution at satellite sub-point) twice hourly and opened completely new avenues for satellite applications (Suomi and Vonder Haar, 1969). The time domain allowed such measurements as wind from cloud motion, cloud growth rates, identification of mesoscale disturbances causing short-term weather phenomena, and many others. In the 1970s the NOAA and DMSP (Defense Meteorological Satellite Program) series of polar orbiter satellites were developed, carrying sophisticated visible and IR radiometers and achieving very high resolution visible and IR imagery (1 km with the NOAA VHRR (Very High Resolution Radiometer) and 0.6 km with the DMSP VHR (very high resolution) sensor). The satellites also carried the first vertical temperature sounders, which allowed remote sensing of the temperature structure of the environment. NASA's Nimbus satellites also provided sounding capabilities including the microwave region and increased both the vertical and the horizontal resolution of the temperature and moisture measurements. The second generation geosynchronous satellites called the SMS-GOES (Synchronous Meteorological Satellite-Geosynchronous Operational Environmental Satellite) (Fordyce *et al.*, 1974) have been developed and are providing both visible (1 km resolu-

tion) and IR (8 km resolution) data twice hourly. The IR capability allows 24 h a day coverage of weather features for the first time. There are two GOES satellites presently in operation, GOES-E (east) positioned at 75°W and GOES-W (west) positioned at 135°W. During the First GARP Global Experiment (FGGE), the world will be girdled by such satellites (two from the United States, one from Europe, and one from Japan).

With the ATS satellites came a data dissemination network called the Satellite Field Service Station (SFSS). These were expanded and received more emphasis once the SMS-GOES satellites were launched. There are six of these SFSSs, which act as hubs or distribution points for photographic data users. Thus, near real-time imagery (20 min after scan) is now available from the GOES satellites to anyone tied into this distribution network. The quantitative digital data from the GOES satellites can be even more valuable both in research analysis and in operations if a suitable system is available to process the data. This paper will discuss how the digital satellite data can be used for weather modification applications and will describe some interactive time domain image-processing systems that have been and are being developed for applications use.

Dennis *et al.* (1973) investigated the usefulness of meteorological satellites in weather modification programs. They concluded that, with the observational requirements needed in a weather modification program, presently available satellite information (as of 1973) could not by itself satisfy these requirements. Their strongest recommendation was that imagery from a geosynchronous satellite with improved spatial resolution and the capability of accurately measuring cloud top temperature (CTT) be provided in real time to the field users. As we have stated, the SMS-GOES satellite systems have satisfied these major requirements and have provided even more in the way of support. We will discuss these present capabilities, as well as point out what satellites may offer in the next decade.

2. Application of satellite information to weather modification programs

a. Summertime cumulus modification experiments

1) CLOUD CLIMATOLOGIES

One of the first objectives in beginning a summer cumulus weather modification program in a given area is determining whether enough convective clouds are present naturally for seeding to take place and what

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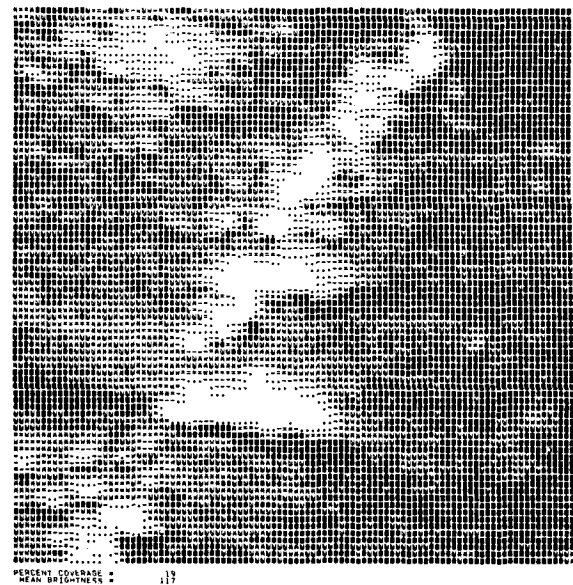
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their natural characteristics are, i.e., isolated cells, well-developed squall lines, etc. The next objective is to determine whether these cumulus clouds are developing with the proper microphysical characteristics so that seeding would change their natural growth pattern in such a way as to increase precipitation.

There are several ways in which one could try to determine the first objective. One would be to take a long history of surface cloud observations to determine how many days convective clouds were observed and the degree of intensity of the day's activity. This is appropriate when a limited area is to be chosen or where a number of surface weather stations are available in a given area to allow complete coverage. This has been attempted by the authors and others and constitutes a very lengthy undertaking. Limited visibility due to rain, low clouds, etc., will severely limit the quality of these types of observations. Also, surface observations could not accurately provide numbers and sizes of convective clouds observed. Another procedure would be to use radar plan position indicator (PPI) data to determine the number of precipitating convective cells, sizes, intensity, rate of growth, and lifetimes (Bark, 1975). Unfortunately, for many of the areas that are being considered for summer weather modification programs, no radar data are available, or the data have not been archived in a format that could be easily processed. Use of radar data is, by its very nature, limited to precipitating clouds. Satellite visible data can sense all convective type clouds above a certain size threshold both before and after they reach the precipitation stage or even if they never precipitate. A comparative study between radar and satellite climatology performed simultaneously may show the ratio of the number of clouds observed (satellite) versus the number of precipitating clouds, which may indicate the potential of a locality for cloud seeding.

The third alternative in determining the seeding potential of a given area is through the use of satellite data. The most useful satellite data in such a study would be geosynchronous satellite data, preferably with both visible and IR measuring capabilities. This type of information has only been available since 1975 when SMS-I was first positioned at 75°W with the VISSR (Visible and Spin Scan Radiometer) on board, providing high-resolution (1 km visible, 8 km IR) data on a half-hour basis. This type of data is the best source of information since the geosynchronous data provide the temporal frequency of the convective activity. The high-resolution visible data allow detection and measurement of very small cumulus clouds, and the IR data allow measurement of CTTs for the larger size clouds. The latter is needed to determine if the cloud has reached a temperature level where supercooled water may be present and seeding can be preformed.¹ Work is now beginning in the archiving of this information in digital form so that a true cloud climatology can be developed

¹ This technique would obviously not be applicable to tropical cumulus undergoing the warm rain precipitation process.



CLOUD	SIZE	MEAN BRIGHTNESS	VARIANCE	STANDARD DEVIATION
1	4	124	0.00	0.00
269	4	147	784.66	16.87
2	30	4.00	4.00	2.00
3	20	4.00	4.00	2.00
4	28	4.00	4.00	2.00
5	24	594.00	24.39	4.93
6	24	24.00	4.00	2.00
7	24	96.00	0.00	0.00
8	124	4.00	4.00	2.00
9	24	35.56	0.00	0.00
10	24	35.56	0.00	0.00
11	24	10.67	0.00	0.00
12	24	46.22	0.00	0.00
13	24	0.00	0.00	0.00
14	24	0.00	0.00	0.00
15	24	0.00	0.00	0.00
16	24	0.00	0.00	0.00
17	24	23.56	0.00	0.00
18	24	0.00	0.00	0.00
19	24	0.00	0.00	0.00
20	24	0.00	0.00	0.00
21	24	0.00	0.00	0.00
22	24	0.00	0.00	0.00
23	24	0.00	0.00	0.00
24	24	0.00	0.00	0.00
25	24	0.00	0.00	0.00
26	24	0.00	0.00	0.00
27	24	0.00	0.00	0.00
28	24	0.00	0.00	0.00
29	24	0.00	0.00	0.00
30	24	0.00	0.00	0.00
31	24	0.00	0.00	0.00
32	24	0.00	0.00	0.00
33	24	0.00	0.00	0.00
34	24	0.00	0.00	0.00
35	24	0.00	0.00	0.00
36	24	0.00	0.00	0.00
37	24	0.00	0.00	0.00
38	24	0.00	0.00	0.00
39	24	0.00	0.00	0.00
40	24	0.00	0.00	0.00
41	24	0.00	0.00	0.00
42	24	0.00	0.00	0.00
43	24	0.00	0.00	0.00
44	24	0.00	0.00	0.00
45	24	0.00	0.00	0.00
46	24	0.00	0.00	0.00
47	24	0.00	0.00	0.00
48	24	0.00	0.00	0.00
49	24	0.00	0.00	0.00
50	24	0.00	0.00	0.00
51	24	0.00	0.00	0.00
52	24	0.00	0.00	0.00
53	24	0.00	0.00	0.00
	3	127	14.22	3.77

FIG. 1. (Top) Gray shade display of a small sector of SMS visible data showing the clouds as the white areas. (Bottom) Computer output giving statistics on the clouds observed in top photo. The size is in satellite element numbers.

(Reynolds and Vonder Haar, 1976). Figure 1 is an example of a computer-derived cloud count using SMS data. The image is reproduced in a gray shade format, and the number and size of each cloud are given.

Prior to the launch of SMS-GOES, the ATS series of satellites provided geosynchronous visible satellite data (4 km resolution at subpoint) on a half-hour basis, so that at least cloud sizes, numbers, locations, and temporal variations could be determined during daylight hours. Several years of ATS data have been used to determine cloud populations and active areas of convection for the three High Plains Cooperative Proj-

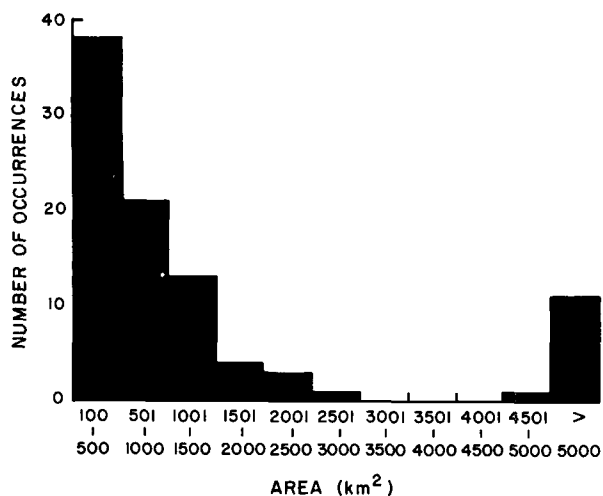


FIG. 2. Cloud size distribution histograms for Miles City, Mont., area as observed from the ATS-3 satellite. The satellite resolution is 113 km².

ect (HIPLEX) field sites (Miles City, Mont.; Goodland, Kans.; and Big Spring, Tex.) being used by the Bureau of Reclamation (see Reynolds and Vonder Haar, 1975). Not only can information be derived about the seeding potential of the sites, but decisions on the optimum location of rain gage networks can also be aided by having this type of information. Figure 2 shows results from a cloud population study done over Miles City, Mont., using ATS-3 data.

Other types of satellite data have also been used for these types of studies. Stodt and Grant (1976) have used data from the low-orbiting, very high resolution (0.6 km) DMSP satellite to obtain cloud numbers and sizes for weather modification sites over the western United States. Although this information provides only a snapshot of the clouds at local noon, even the very small cumulus can be detected with these data (see Table 1).

Another aspect of using satellite information for determining cloud climatologies is that the general numbers, sizes, growth patterns, and also cirrus extent will be known for both the target site and areas downwind. This will aid in determining to what extent seeding may affect the normal convective activity both at the site and downwind of the site. This will be discussed in more detail in a later section.

There are problems in using satellite data for developing cloud climatologies as there are with other techniques. Cirrus clouds can obscure lower clouds, and ground resolution problems may cause the smaller clouds to be missed. Computational time is extensive in processing the digital satellite data. Determination of cloud thresholds is also difficult. A man-computer interactive processing system is necessary for this type of study for accurate results to be obtained. However, we believe that the satellite provides a valuable tool to help assess the seeding possibilities in a given area.

2) REAL-TIME OPERATIONAL SUPPORT

As was mentioned earlier, near real-time high-resolution SMS-GOES satellite photo imagery is available to operational field sites at half-hour intervals. This allows qualitative analysis of both synoptic scale cloud features, as well as smaller mesoscale convective cloud developments to aid in the "nowcasting" of target site conditions for deploying aircraft or starting seeding operations. Reynolds and Matthews (1976) and Reynolds and Vonder Haar (1976) have described how geosynchronous satellite information has aided in supporting operations for HIPLEX (Bureau of Reclamation). It was noted that such convective triggering mechanisms as dry lines, vorticity centers, and fronts could be defined using the imagery and used for making the day's forecast of convective activity (Fig. 3; see also Purdom (1974)). Since all of the HIPLEX sites are located east of mountainous terrain, some of the convection passing over the sites is generated over the mountains. The generation and movement of these cells and whether or not they are increasing or decreasing in intensity can easily be monitored using the satellite imagery. Enhanced IR imagery can provide this type of information by monitoring CTTs to see if they are increasing or decreasing. Figure 4 is an example of this type of imagery, and the change in CTTs can be noted by the change in gray level of the tops (see Corbell *et al.* (1976) for details).

3) USE OF DIGITAL AND IMAGE SATELLITE DATA IN POSTEXPERIMENT ANALYSIS

Operations debriefing and evaluation. Much of the postanalysis work to date has been in using imagery to help locate certain synoptic or mesoscale features that may have influenced an experimental day's activities and to monitor their time histories. Reynolds and

TABLE 1. Mean values for days with convective clouds, July 1974

	Miles City, Mont.	Goodland, Kans.	Big Spring, Tex.	NE Colorado*	Palmer Lake Divide	South Park	Upper Arkansas River Valley†
Average cloud cover, %	4.9	10.1	8.3	4.4	11.1	20.3	27.0
Average number of clouds per 10 ⁴ km ²	4	6	9	8	7	18	19
Average size of cloud, km ²	144.1	172.1	87.3	54.7	158.1	115.2	140.5

* National Hail Research Experiment.
† Leadville and Buena Vista.

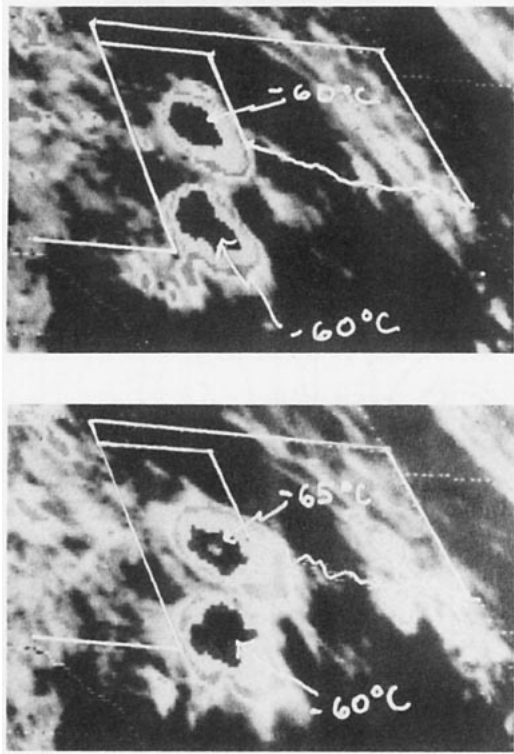


FIG. 4. (Top) The 0115 GMT, 22 June 1976, enhanced IR image showing two large thunderstorms located in the Texas panhandle. (Bottom) The 0215 GMT, 22 June 1976, enhanced IR image showing that the northern storm has increased in height while the southern storm appears to have remained constant.

digital rather than photo image data for these quantitative studies. There are several reasons for this:

- 1) Digital data can be earth located, "navigated," accurately for proper location of target sites and collocation with other data (Smith and Phillips, 1972).
- 2) Data can be normalized for sun angle changes and viewing angles using bidirectional reflectance models (Sikula and Vonder Haar, 1972).
- 3) Data can be directly input into digital processing systems (see Section 4) for analysis, and this allows computer mixing of several different types of data as well as time-sequencing capabilities.

Probably the most important parameter that must be measured in any weather modification program is precipitation. Given an area as large as the High Plains region of the United States, it is very difficult to have enough rain gages available to obtain good estimates of rainfall. Radar coverage is very limited in these regions but is the next most accurate tool for use in rainfall measurements. However, recent studies in HIPLEX show a single $Z-R$ relationship is very difficult to obtain. Over the past several years, work has been done in attempting to estimate rainfall from visible and IR satellite data (Griffith *et al.*, 1976; Follansbee and Oliver, 1975; and Scofield and Oliver, 1977). In an attempt to extend some of this work, we compared digital SMS

satellite data (available every 7.5 min) to digital radar data over the Goodland/Colby HIPLEX sites (Negri *et al.*, 1976) for 28 August 1975 during weak convective activity. The main conclusions from this study were that:

- 1) with use of a reflected brightness thresholding technique, precipitating versus nonprecipitating clouds may be defined;
- 2) a lag of as much as 20 min may elapse between the time this brightness threshold is reached and a radar echo is noted;
- 3) brightness does not seem to correlate well with any radar echo parameters such as area, volume, or intensity, but it does seem to be related to cloud size, and the center of maximum brightness locates well with the maximum radar reflectivity during the growth stage of the storm;
- 4) the areal growth rate of a cloud may relate to storm severity and to determine these growth rates, rapid scan data are necessary (5–15 min interval data).

These studies are in their very formative stages, and much work is needed to test the possibility of this procedure.

In relating cloud visible brightness to cloud parameters of interest, a separate study was needed to determine the relationship between changes in cloud brightness and simple changes in the cloud's vertical or horizontal extent (Reynolds *et al.*, 1978). This is a very important problem if we are going to use satellite brightness data to quantitatively measure changes in intensity of precipitation. Preliminary results seem to indicate that geometric factors outweigh change in cloud microphysical characteristics in influencing cloud brightness changes. McKee and Cox (1974, 1976) have discussed this problem in detail on a more theoretical basis, and the question must be studied further.

One other aspect of using quantitative satellite data is for input to and verification of cumulus cloud models (Kreitzberg, 1976). One-, two-, and even three-dimensional cloud models are being used in many weather modification programs. Ideal input to these models requires a closely spaced rawinsonde network for determining the atmospheric temperature and moisture structure and the vertical and horizontal wind components. With the advent of vertical temperature sounders on NOAA polar-orbiting satellites, high horizontal resolution (approximately every 70 km) temperature and moisture measurements became available for use in these types of models. Hillger and Vonder Haar (1977) have used VTPR (Vertical Temperature Profile Radiometer) data in conjunction with the conventional rawinsonde network to obtain mesoscale temperature and moisture fields over the High Plains. Figure 5 is an example of the use of VTPR data to derive mesoscale fields of temperature and precipitable water. (Although vertical resolution from satellite data is poor, having gradients in these parameters over short horizontal distances provides much information at the mesoscale.)

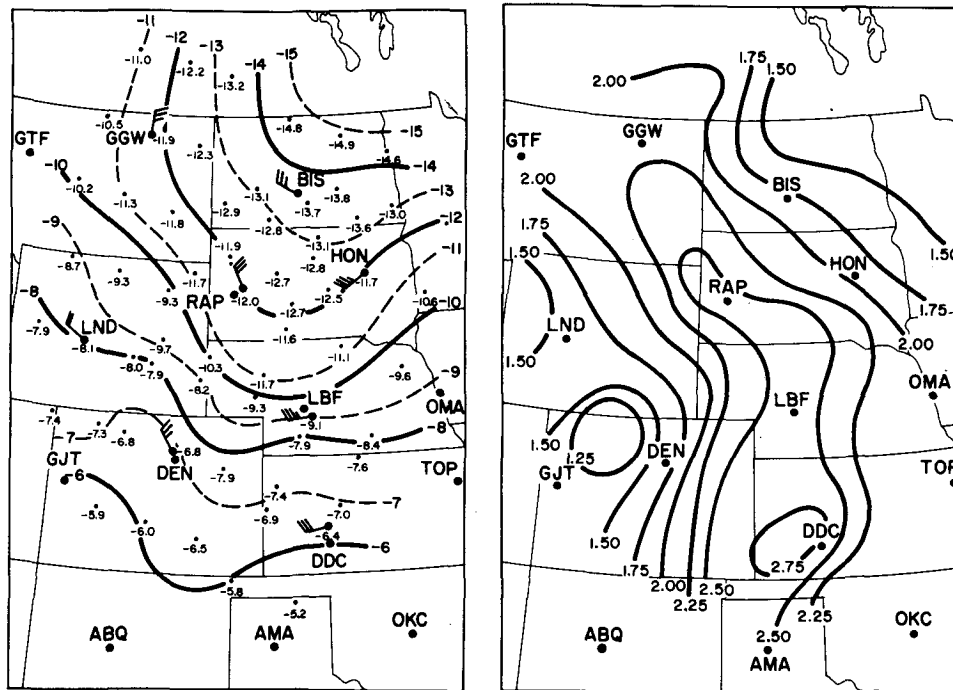


FIG. 5. (Left) Combined NWS and VTPR 500 mb temperature (in degrees Celsius) field for 9 August 1973. The thermal winds for the 700–300 mb layer are shown as derived from the VTPR data. (Right) VTPR-derived total precipitable water field (in centimeters) for 9 August 1973 at 1700 GMT.

This type of information is now being integrated into HIPLEX so that it will be available in real time for input into cloud models or for analysis of mesoscale features likely to cause convective activity. When GOES-D is launched in the 1980s, it will provide the first geosynchronous vertical temperature sounder data, allowing soundings to be made at rapid intervals over small areas where convective activity is likely to occur.

4) SPECIALIZED APPLICATION AREAS

Tropical cumulus modification study. Two general areas can be specified when discussing tropical weather modification activities. The first includes such activities as the Florida Area Cumulus Experiment (FACE) (Woodley *et al.*, 1976), which is involved in the seeding of tropical cumuli to increase rainfall. The seeding hypothesis of the FACE program is to increase the organization of the convective activity by seeding certain elements of a cloud line increasing the dynamics of the system so that it may precipitate for a longer period of time. As was mentioned earlier, Griffith *et al.* (1976) have been using satellite data to determine rainfall over the target area for a limited data sample. Other uses of satellite data are to simply pinpoint areas of existing cloud lines or clusters so that seeding aircraft can be deployed to these areas in time for seeding to occur. With the IR data now available from SMS-GOES it is possible to monitor these cloud lines and note any changes in CTT during seeding or the extent of cirrus for the seeded versus non-seeded storms. These IR data

will also allow comparison to radar data to further explore satellite-rainfall relationships.

The other specific application area that is immediately thought of is that of hurricane modification. Satellite data allow the only consistently available monitoring system for determining storm strength, motion, and the changes in these parameters. A more direct verification method to evaluate hurricane modification can be accomplished by using geosynchronous satellite data to determine wind speeds from cloud motions within the storm system. With a clear view of the eye, measurements can be made of cloud motions along the eye wall (Gentry *et al.*, 1976). Dvorak (1975) has developed a technique for determining the intensity of tropical disturbances that can be used as a type of climatology when seeding occurs to determine if any radical effects have taken place. Project Stormfury, which is to begin again in 1978, will rely heavily on the SMS-GOES satellites for the monitoring of these storms as well as for the evaluation of the experiment.

Extra-area effects (downwind, etc.). The question of whether seeding effects are limited to the local area in which they are applied has been discussed as a political and scientific issue since weather modification activities began. There are several ways in which summertime cumulus activity and the modification of this activity can affect other areas outside the proposed target site. One method is that the cirrus outflow from the seeded storms could be more extensive than in non-seeded

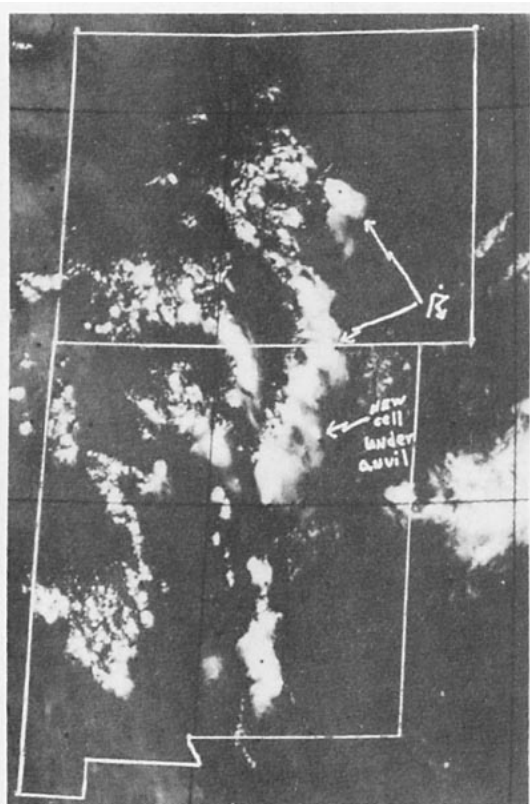


FIG. 6. DMSP 0.6 km visible image showing thunderstorm development along the front ranges and mountains of Colorado and New Mexico. Note the cirrus blow-off and the new cell under cirrus.

cases; this could decrease the local heating under this cirrus canopy, thus reducing convection. Satellites provide a complete view of all areas both in and out of the target areas and can easily monitor the cirrus outflow of both the seeded and non-seeded cells to determine any differences in cirrus extent and whether convection is growing through the cirrus canopy or suppressed in areas where the canopies existed. It may also be that the cirrus can act as a natural seeding device by injecting large amounts of ice crystals into developing cumulus clouds to increase cloud growth. Figure 6 is an example of a DMSP 0.6 km visible image showing convection along the continental divide and front range areas of Colorado and New Mexico. Note the extent of cirrus outflow of these naturally forming clouds and also the new cell development under the cirrus outflow of an earlier cloud. It is this type of monitoring that can aid in the analysis of extra-area effects of seeding programs.

b. Wintertime cloud modification experiments

1) COLD OROGRAPHIC AND PACIFIC FRONTAL RAINBAND CLOUD MODIFICATION

The potential for increased precipitation from super-cooled orographic stratiform and frontal rainband precipitation clouds is well established (Grant and Mielke, 1967; Elliott *et al.*, 1971; Chappell *et al.*, 1971; Grant

and Elliott, 1974; Gagin and Neuman, 1977). In fact it may be that these types of clouds offer the best possibility for seeding and for increasing precipitation over those areas where they exist. Some of the research experiments that have dealt with this type of cloud seeding are:

Group	Area for Field Studies
EG&G Inc.	San Juan Mountains of southern Colorado
Colorado State University	Central Colorado (Climax)
CSIRO	Tasmania
Desert Research Institute	Sierra Nevada
E. Bollay Assoc.	Park Range in northwest Colorado
Fresno State University	Sierra Nevada
Montana State University	Bridger Range in Montana
New Mexico State University	Jemez Mountains of New Mexico
North American Weather Consultants	Mountains near Santa Barbara, Calif.
Utah State University	Wasatch Mountains of northern Utah
University of Washington	Cascade Mountains in Washington
University of Wyoming	Elk Mountain and Wind River Mountains in Wyoming

Grant and Elliott (1974) have summarized the results from many of these studies and others to show that seeding effectiveness is highly dependent upon CTT (see Table 2.) Their studies show that increases in precipitation can be expected when seeding is performed on clouds with CTTs in the range of -10°C to -25°C . For clouds colder than -28°C , decreases in precipitation can actually occur after seeding. During many of these pro-

TABLE 2. Santa Barbara 2 (1967-70) average precipitation as a function of estimated CTTs for seeded and non-seeded cases.*

CTT, $^{\circ}\text{C}$	Seeded		Non-Seeded		Precipitation Ratio Seed/No-Seed
	Precipitation, mm/band	No. of Cases	Precipitation, mm/band	No. of Cases	
-17	10.7	13	5.1	22	2.10
-18	18.8	12	6.4	23	2.96
-19	16.5	24	6.4	21	2.60
-20	12.5	22	6.6	17	1.88
-21	9.9	21	6.4	14	1.56
-22	10.4	21	7.6	11	1.36
-23.5	8.6	10	7.1	8	1.21
-24.5	10.2	10	8.9	8	1.14
-26	11.4	10	9.7	10	1.18
-27.5	15.8	9	12.5	7	1.26
-28.5	15.0	7	8.9	5	1.40
-31	9.4	6	5.6	4	†
-33.5	7.4	3	5.1	2	†

* Values of precipitation for moving means of two temperature steps of 2.5° - 3°C are centered on the indicated CTT. (Reproduced from Grant and Elliott, 1974).

† Sample too small to be significant.

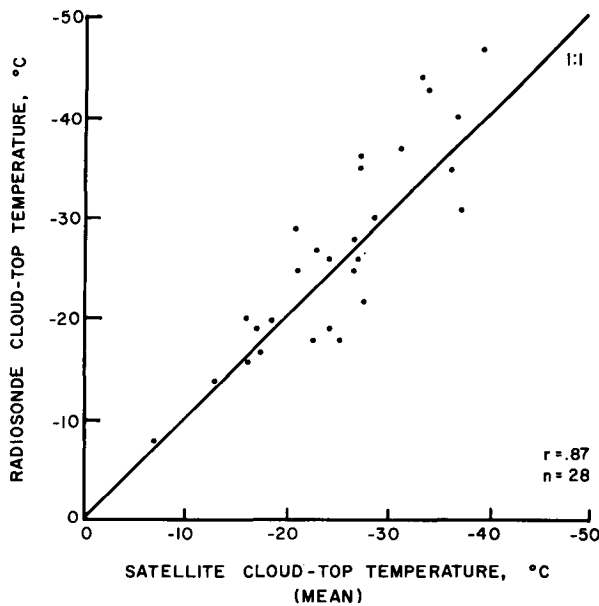


FIG. 7. Relationship between mean satellite-observed CTTs and radiosonde-determined CTTs for the entire data set of 1973–74 for the San Juan Mountain area.

grams, estimates of CTT were derived from either rawinsonde data or interpolated 500 mb temperatures. These have frequently proved to be inadequate in that only 3–5 rawinsondes can be launched per day and cloud tops cannot always be adequately deduced from the soundings alone. In addition, the 500 mb temperatures do not represent CTTs in many instances. As was stated earlier, Dennis *et al.* (1973) noted that one of the most beneficial uses of satellite data would be in monitoring CTTs from a geosynchronous satellite to provide half-hour information on CTT and its changes.

Real-time operational support. The term “opportunity recognition” has been used in the field of weather modification to designate those environmental conditions in which it has been determined that seeding will have positive effects. As we have pointed out, the CTT is a very important parameter when discussing these types of cloud systems. Another important question of “opportunity recognition” concerns the spatial and temporal location of seedable clouds. The inhomogeneities of actual clouds and their seedability are so great that considerable variability generally exists over even moderately sized weather modification targets. The ability of IR satellite data to provide CTT information has been demonstrated by Dumont *et al.* (1974) in a preliminary study using NOAA polar orbiter satellite data. Using the IR portion (10–12 μm) of the scanning radiometer (SR) on the NOAA satellite, they were able to measure CTTs for clouds over the San Juan Mountain area of Colorado during the Bureau of Reclamation’s Colorado River Basin Pilot Project. Figure 7 is a comparison of satellite-determined CTT and radiosonde-determined CTT for all cases available. The results show that on the

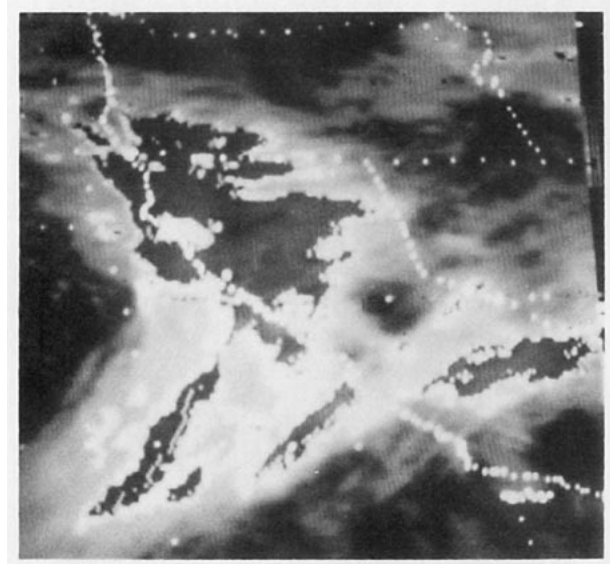


FIG. 8. Enhanced GOES-W IR image from a digital display for 1745 GMT, 15 March 1977, showing a Pacific storm entering the California coastal region. Darker gray represents CTTs from -43° to -47°C ; medium gray, from -39° to -43°C ; and white, from -31° to -39°C .

mean, the satellite observes a warmer cloud top ($+1.8^{\circ}\text{C}$) than does the radiosonde. Although such problems as time differences between satellite and radiosonde observations, cirrus clouds overlying the orographic cloud, and cloud emissivity problems affect these comparisons, this preliminary study demonstrated the general feasibility of using satellites for this type of measurement. A second season (1974–75) of data is now being processed; NOAA polar orbiter data, again for the San Juan Mountain region, are being used. During this season, the first geosynchronous IR data became available from SMS-1 positioned at 75°W . Digital data from this satellite are available, and maps of CTT over the San Juan Mountains can be generated on a half-hour basis for a 24 h period.

To provide the real-time support necessary for field operations there are several methods in which the cloud top information could be provided. The first is using the enhanced IR imagery data where a specific gray scale would denote clouds with temperatures in the seeding window. These images would be available to the forecaster on a half-hour basis so that he could decide not only in what locations out of the entire storm complex seeding should take place but also when to begin and end the seeding operations. This is particularly important since several studies have strongly indicated that the main seeding effect is an increase in the duration of precipitation (Chappell *et al.*, 1971; Gagin and Neuman, 1977).

A second method would be to strip out the specific area of interest for the seeding activities from the digital data taken directly at the satellite ground station and either to map this information with a computer printer or to display the data on a CRT using a video recording

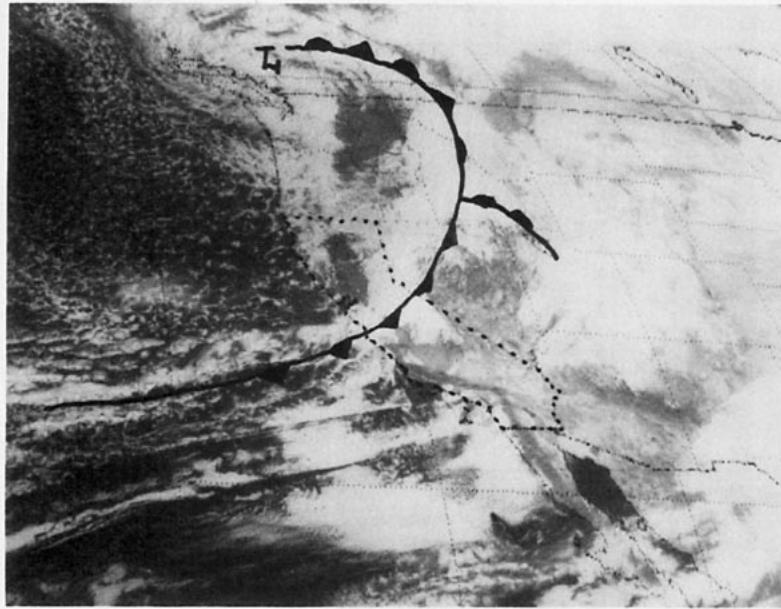


FIG. 9. SMS-2 2 km visible image for 1645 GMT, 9 March 1977, showing a Pacific frontal system situated over the Sierra Nevada.

system. These types of data could be transmitted to a field site by phone line to give the forecaster a constant update of CTTs. More on this video-digital display capability will be given in Section 3.b.

Use of digital satellite data in postexperimental analysis. During the postexperiment phase of the seeding program the digital SMS-GOES imagery collected can be used to stratify each day's seeding event into CTT categories. This is being done for the 1974-75 Colorado River Basin Pilot Project experiment using NOAA and SMS data and will be done for the Bureau of Reclamation's Sierra Cooperative Pilot Project, which began during the 1976-77 winter season over the central Sierra Nevada of California. The Bureau of Reclamation is now involved in a preliminary investigation of the characteristics and natural variability of convective rainbands as they impinge on the Sierra Nevada of California. In cooperation with the Bureau of Reclamation, Colorado State University has recorded digital SMS full resolution visible and IR data continuously from the time the bands are just off the coast of California to their passage through the Sierra Nevada. We hope to obtain information on the capability of the satellite to determine the accuracy to which the top temperatures of these rainbands can be measured, how these temperatures vary with time, and the effects topography has on these bands (see Fig. 8). As verification, a cloud top aircraft is being flown over these bands to estimate their height and temperature. Photographs will be taken, and the presence of clouds, such as cirrus, that may overcast these bands will be noted. As was done for the summertime projects, radar-satellite comparisons will be made to determine if any relationships exist and

whether the satellite data can be used to quantitatively determine precipitation amounts.

Not only can CTTs be determined, but an assessment of the types of synoptic situations that give rise to seedable clouds can also be determined through the use of satellite imagery and conventional meteorological data. The satellite allows an overall view of the synoptic situation (Fig. 9), which can allow categorization of optimum seeding situations and can be used as a forecasting aid for future events.

The same application of the satellite data can be made in the wintertime program as was made in the summertime programs. This relates to the relative difference in cloud characteristics of the seed/no-seed events as well as determining any biases in the randomized seeding events ("equality of draw"). For the wintertime clouds, such observable cloud features as stratiform layers versus presence of imbedded convection, CTT variation and magnitude, and visible cloud appearance (i.e., fuzzy (ice present?) versus distinct cloud edges (possibly only supercooled water clouds), etc.) could be analyzed for these different days. Chappell *et al.* (1971) have found that for the Climax Experiment, seeding tended to increase the duration of precipitation rather than the intensity of the precipitation event. It may be that by either monitoring the CTT (height) fluctuation through a storm period or determining the duration of the orographic clouds' fuzzy appearance, the satellite data might be used to decide if the precipitation event is of longer duration or more intense in nature.

For determining whether a true random sample has been chosen for a given experimental period, the satellite information can provide measurements of overall cloud extent both in and out of the target region. The

mean CTTs for the entire storm complex can be determined, and the direction and speed of cloud motions over the mountain barriers and indications of band structures (associated with either fronts or mesoscale features) can be observed for all seeding events. If any biases are present on the seed or no-seed days, then they can be removed before final analysis. Again, these same measurements might aid greatly in a covariate determination technique.

2) SPECIALIZED WINTERTIME APPLICATIONS

As was mentioned with the summertime program, there has been concern with the effects downwind from the wintertime seeding programs. Brier *et al.* (1974) review much of the work carried out to date in determining the downwind effects from seeding cold orographic clouds. Many of the results to date show varying degrees of effect, from large increases to slight decreases. Brown *et al.* (1976) have recently summarized the results of the seeding program over Santa Barbara, Calif., where Pacific frontal rainbands were seeded over a 7-year period. Their conclusions stated that the primary cause of extra-area effects is probably a dynamic intensification of organized convective activity that produces increases in precipitation ~ 150 km downwind from the seeding source and $\sim 30^\circ$ to the right of the 700 mb wind flows. With satellite data it should be a fairly straightforward problem to monitor this area in an effort to determine whether the activity is more intense or continues for a longer period of time.

Mulvey and Grant (1976) have proposed a separate mechanism for extra-area effects downwind from the Climax Experiment in Colorado. Their hypothesis is that seeding material carried up into the orographic cloud is not entirely used and is transported downwind along with unused ice crystals. The seeding materials and ice crystals that survive the downwind transport can seed lower upslope cloudiness along the Front Range of the Rockies, which are warmer and deficient of the proper number of ice nuclei for efficient precipitation. This inadvertent seeding then should supply the cloud with an increased number of nuclei for increased precipitation. Scheetz and Grant (1976) have prepared a climatic estimate of the frequency with which High Plains upslope clouds are seedable. With both visible and IR satellite data it is possible to monitor the ice blow-off from the orographic cloud. In the area where this intersects the upslope cloudiness, a change in both the visible appearance of the cloud and in top temperature can be monitored to see if this seeding has any effect. Without aircraft data this is the only way to monitor this type of extra-area effect directly.

3. Present and developing technology in satellite observation systems and data processing

a. Present and near future capabilities

We have discussed many of the present capabilities of meteorological satellites as they relate to existing weather modification activities. However, we have certainly not

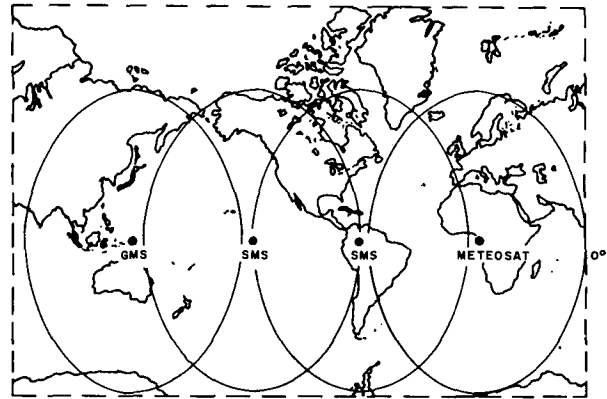


FIG. 10. Proposed geosynchronous satellite coverage for the late 1970s showing that all proposed WMO Precipitation Enhancement Experiment sites will be in view during all local times.

discussed all the widely varying activities and uses of the data. There is one important area that should be discussed as it relates to the World Meteorological Organization (WMO) Precipitation Enhancement Experiment (PEP) (List, 1976). Site selection is one of the first priorities of the WMO. Although there are many political, social, and economical influences on these decisions, one overwhelming factor must be the requirement for "seedable" clouds to exist at the site frequently enough that seeding can be done. The satellite data can observe the presence of clouds and their appearance, i.e., stratified (stable) versus convective (unstable) over a particular site, aiding in the decision of whether to use a static (microphysical) seeding approach or a dynamic seeding approach. As was mentioned earlier, satellite data can provide this type of information on a worldwide basis. There exist many years of polar orbiter data with afternoon cross-over times that can and have been used to monitor convective activity. Also, on board many of the satellites are IR sensors allowing the measurement of CTTs of clouds large enough to fill the field of view of the sensor, so that it can be determined whether the clouds are cold enough for seeding materials to be effective.

By 1979, in cooperation with FGGE there will be four, possibly five, geosynchronous satellites girdling the globe, (Fig. 10), allowing for the first time high spatial and temporal frequency satellite data continuously for the whole globe. These types of data will prove invaluable in assessing future weather modification sites both for summer and for winter programs.

We should mention here that there is one other important use of the SMS/GOES satellite that can be a real-time source of information besides providing satellite visible and IR data. This involves the communications channels on board the satellite that can interrogate, every half-hour, the transmitters of ground-based data collection platforms (DCPs). Such observations as temperature, humidity, and wind can be obtained and transmitted down to the ground station and displayed

on the aforementioned remote terminal. Also, rain gage data or stream gage data can be monitored, especially for analysis of seeding effects or for flash flood alerts and snowpack conditions, to see if additional seeding or suspension of seeding is necessary in a given area. This capability of SMS should be integrated with the digital imagery to provide extremely useful and timely information to all aspects of field operations and forecasting.

b. Real-time satellite data analysis and display systems

As has been mentioned in the previous discussions, of equal importance to the gathering of new data from new systems is the development of quantitative digital data analysis methods. These digital data allow the monitoring of cloud brightness, CTTs, and cloud motions. In addition, accurate navigation of the data can be performed through the recording of the line documentation being sent by the satellite (Smith and Phillips, 1972). This includes the housekeeping information of the satellite such as the geometry of the earth, sun, and satellite and time marks for each scan line. This information can then be input to an analytic model for navigation of each visible image to ± 1 (1 km) satellite element (relative picture to picture). Knowing the earth, sun, and satellite locations also allows brightness normalization to be made, which can account for changing sun angle effects and can try to compensate for cloud anisotropy.

Generally, satellite data, to be of maximum usefulness, must be available in real time. Over the past several years, development of digital data-processing systems with man-computer interactive capabilities and CRT display have been developed. The following is a list of several of these systems now in use throughout the United States:

- 1) AOIPS—Atmospheric and Oceanographic Information Processing System (NASA Goodard Space Flight Center);
- 2) LARS—Laboratory for Applications of Remote Sensing (Purdue University);
- 3) McIDAS—Man Computer Interactive Data Access System (University of Wisconsin, Space Science and Engineering Center);
- 4) MMIPS—Man-Machine Interactive Processing System (NOAA/NESS);
- 5) ADVISAR—All Digital Video Imaging System for Atmospheric Research (Colorado State University);
- 6) ESIAC—Electronic Satellite Imaging Analysis Console (Stanford Research Institute).

These systems, when located with the satellite ground station, can provide real-time processing and analysis of cloud growth rates, cloud motions, change in top height, etc., that can be useful to field operation. (Real-time navigation is now in use at the Direct Readout Ground Station at the Space Science and Engineering Center in Wisconsin.) These systems operate through input of digital satellite data, which can be stored on

digital systems and displayed sequentially through rapid refresh of a CRT monitor. Thus, 2–3 h of satellite data can be “looped” through, allowing cloud motions to be determined and thus providing information on meso-scale divergence, convergence, etc. Also, the operator can interact directly with the data to enhance through color or black and white shading methods; he can zoom in on small features or rotate or translate the image and can determine, through use of a joystick and cursor, CTT or brightness of any cloud he so desires. Through recent and ongoing advances in solid state electronics, these types of systems can be remotely placed in the field away from ground stations with just a telephone hook-up to a keyboard and CRT necessary for data access and manipulation. At the present time, work is under way in developing such a system that can meet the needs of not only weather modification programs but also severe storm forecasters and many other satellite data users, including industrial meteorologists (Bristor and Raynore, 1977).

4. Future advances in satellite observing systems

Future advances in satellite technology should be as impressive and as rapid as those that took place during the last 10 years. One important new development that could provide dramatic technological advances will be the Space Shuttle. The Space Shuttle will put much larger sensor payloads into orbit either by constructing them in space or by launching them on the Shuttle and then boosting them into geosynchronous orbit by space taxis. Thus, large microwave (passive and active) antenna systems can be launched allowing direct measurements of precipitation over land and oceans and also allowing measurements of water vapor profiles at very high horizontal resolution (~ 10 km) and having 2–5 km resolution in the vertical. Shenk and Kreins (1975) discuss some of these future breakthroughs that will come about in the 1980s.

Not all of the advances will have to wait for the Space Shuttle. Planned for launch around 1981 will be the GOES-D satellite equipped with VAS (VISSR Atmospheric Sounder). This will be the first sounder placed into geosynchronous orbit and will provide soundings at ~ 30 km spacing every half hour for a 750 km north-south latitude band and entire earth width. The VAS will have nine channels, sensing temperatures (resolution to $\pm 2.5^\circ\text{C}$) below the 100 mb level (thus temperature every 100 mb) and two water vapor channels for determining precipitable water.

The next generation of satellites being considered will be Stormsat (Shenk and Kreins, 1975), which will improve both the imaging and the sounding capabilities of the GOES series of satellites. This will be a three-axis stabilized spacecraft, which means it will always be pointing toward the earth and will be mechanically stepped both in the east-west and in the north-south direction. Thus, very rapid scan information over a 750 km² area will be available. Also, soundings using microwave channels can be made in overcast regions with 2° – 3°C

temperature resolution at a 50 km interval every 30 min, and these microwave channels will allow moisture determination (10–15% accuracy in relative humidity) for 30 km intervals every 30 min. This type of information can be used directly in two- and three-dimensional numerical cloud models for both initialization and verification.

There are now even plans to fly radiometers that will determine something about a cloud's physical properties, i.e., cloud top pressure level, the density and phase (i.e., ice versus water) of condensed water in the clouds, a drop-size parameter, and the cloud thickness, both optical and geometrical.

5. Summary

We believe that satellite information has the greatest utility for weather modification application when it is incorporated into a research operation along with other data sets. Over the past several years, satellite technology and analysis technology have improved greatly. The last section of this paper was designed to show the projected advances that may take place in the next decade, even though they may be overly optimistic. Satellite sounder systems offer one of the highest potentials for application to weather modification programs, and it is hoped that, through the use of multispectral instruments, a high degree of vertical (albeit still crude compared to radiosonde) and horizontal resolution can be obtained, both in temperature and in moisture. Continued research is needed on quantifying observed features from the satellite image; quantification must be such that the numbers can be incorporated into numerical models to help predict cloud development, seeding potential, and possible extra-area effects.

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References

- Bark, D. L., 1975: A survey of the radar echo population over the western Kansas High Plains. Vols. 1 and 2, Dept. of Physics, Kansas Agric. Exper. Station, Kansas State Univ., Manhattan, Kans.
- Brier, G. W., L. O. Grant, and P. W. Mielke, 1974: The evidence for extra-area effects from purposeful weather modification projects. *Preprints, Fourth Conference on Weather Modification (Ft. Lauderdale)*, AMS, Boston, pp. 510–515.
- Bristor, C. L., and W. L. Raynore, 1977: Digital satellite imagery in industrial meteorology. *Bull. Amer. Meteor. Soc.*, **58**, 480–487.
- Brown, K. J., R. D. Elliott, and J. R. Thompson, 1976: Seeding convective bands in winter storms and the observed large scale effects. *Proceedings of the Second WMO Conference on Weather Modification, 2–6 August, Boulder, Colo.*, WMO, Geneva, pp. 465–472.
- Chappell, C. F., L. O. Grant, and P. W. Mielke, Jr., 1971: Cloud seeding effects on precipitation intensity and duration of wintertime orographic clouds. *J. Appl. Meteor.*, **10**, 1006–1010.
- Corbell, R. P., C. J. Callahan, and W. J. Kotsch, 1976: *The GOES/SMS User's Guide*. NOAA/NESS, Washington, D.C.
- Dennis, A. S., P. L. Smith, and K. R. Biswas, 1973: Use of meteorological satellite observations in weather modification programs. Rep. 73-6, Inst. of Atmos. Sci., South Dakota School of Mines and Technology, Rapid City, S.Dak. (NTIS #N73-22583.)
- Dumont, R. J., D. W. Reynolds, L. O. Grant, and T. H. Vonder Haar, 1974: Determining the seedability of winter orographic clouds from satellite observations. *Preprints, Fourth Conference on Weather Modification (Ft. Lauderdale)*, AMS, Boston, pp. 454–461.
- Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**(5), 420–430.
- Elliott, R. D., P. St. Amand, and J. R. Thompson, 1971: Santa Barbara pyrotechnic cloud seeding test results, 1964–1970. *J. Appl. Meteor.*, **10**, 785–795.
- Follansbee, W. A., and V. J. Oliver, 1975: A comparison of infrared imagery and video pictures in the estimation of daily rainfall from satellite data. NOAA Tech. Memo., NESS 62, Washington, D.C., 14 pp.
- Fordyce, D. V., R. J. Wirth, and W. E. Shenk, 1974: The synchronous meteorological satellite (SMS) system. *Preprints, Sixth Conference on Aerospace and Aeronautical Meteorology (El Paso)*, AMS, Boston, pp. 158–164.
- Gagin, A., and J. Neuman, 1977: The second Israeli cloud seeding experiment—The effects of seeding on varying cloud populations. Dept. of Atmos. Phys., Hebrew Univ., Jerusalem, 10 pp.
- Gentry, R. C., E. Rodgers, W. E. Shenk, and V. Oliver, 1976: Deriving winds for hurricanes using short interval satellite imagery. *Preprints, Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites (Melbourne, Fla.)*, AMS, Boston, pp. 115–118.
- Grant, L. O., and R. D. Elliott, 1974: The cloud seeding temperature window. *J. Appl. Meteor.*, **13**, 355–363.
- , and P. W. Mielke, 1967: A randomized cloud-seeding experiment at Climax, Colo., 1960–65. *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*, Vol. 5, University of California Press, Berkeley, pp. 115–132.
- Griffith, D., W. L. Woodley, S. Browner, J. Teijero, M. Maier, D. W. Martin, J. Stout, and D. Sikdar, 1976: Rainfall estimation from geosynchronous satellite imagery during daylight hours. NOAA Tech. Rept., ERL 356-WMPO 7, 106 pp. (NTIS #PB-254 652/1G1.)
- Hillger, D. W., and T. H. Vonder Haar, 1977: Deriving mesoscale temperature and moisture fields from satellite radiance measurements over the United States. *J. Appl. Meteor.*, **16**(7), 715–726.
- Kreitzberg, C. W., 1976: Interactive applications of satellite observation and mesoscale numerical models. *Bull. Amer. Meteor. Soc.*, **57**(6), 679–685.
- List, R., 1976: Objectives and status of the WMO precipitation enhancement project (PEP). *Proceedings of the Second WMO Scientific Conference on Weather Modification*, WMO, Geneva, pp. 445–453.
- McKee, T. B., and S. K. Cox, 1974: Scattering of visible radiation by finite clouds. *J. Atmos. Sci.*, **31**, 1885–1892.
- , and —, 1976: Simulated radiance patterns for finite and cubic clouds. *J. Atmos. Sci.*, **33**(10), 2014–2020.
- Mulvey, G. J., and L. O. Grant, 1976: A physical mechanism of extra-area effects from the Climax orographic cold cloud seeding experiment. *Proceedings of the Second WMO Scientific Conference on Weather Modification*, WMO, Geneva, pp. 477–479.

- Negri, A. J., D. W. Reynolds, and R. A. Maddox, 1976: Measurements of cumulonimbus clouds using quantitative satellite and radar data. *Preprints, Seventh Conference on Aerospace and Aeronautical Meteorology and Symposium on Remote Sensing from Satellites (Melbourne, Fla.)*, AMS, Boston, pp. 119-124.
- Purdum, J. F., 1974: Satellite imagery applied to the meso-scale analysis and forecast. *Preprints, Fifth Conference on Weather Forecasting and Analysis (St. Louis)*, AMS, Boston, pp. 63-68.
- Reynolds, D. W., and D. A. Matthews, 1976: Real time satellite support for the High Plains cooperative experiment. *Proceedings of the Second WMO Scientific Conference on Weather Modification*, WMO, Geneva, pp. 497-502.
- , and T. H. Vonder Haar, 1975: Satellite support to the HIPLEX activities for 1975. Final report to the Bureau of Reclamation, contract no. 14-06-D-7630. (NTIS #PB-250 563/4G1.)
- , and —, 1976: Satellite support to the HIPLEX activities for 1976. Annual report to the Bureau of Reclamation, contract no. 6-07-DR-20020, Denver Federal Center, Denver, Colo.
- , T. B. McKee, and K. S. Danielson, 1978: Effects of cloud size and cloud particles on satellite observed reflected brightness. *J. Atmos. Sci.*, **35**, 160-164.
- Scheetz, V. R., and L. O. Grant, 1976: Satellite observation of seedable upslope cloud systems. *Proceedings of the Second WMO Scientific Conference on Weather Modification*, WMO, Geneva, pp. 491-496.
- Scofield, R. A., and V. J. Oliver, 1977: A scheme for estimating convective rainfall from satellite imagery. NOAA Tech. Memo., NESS 86, Washington, D.C.
- Shenk, W. E., and E. R. Kreins, 1975: The NASA severe storm program. *Preprints, Ninth Conference on Severe Local Storms (Norman, Okla.)*, AMS, Boston, pp. 468-473.
- Sikula, G. J., and T. H. Vonder Haar, 1972: Very short range local area weather forecasting using measurements from geosynchronous meteorological satellites. Atmos. Sci. Pap. no. 185, Colorado State Univ., Ft. Collins, 73 pp.
- Smith, E. A., and D. R. Phillips, 1972: Automated cloud tracking using precisely aligned digital ATS pictures. *IEEE Trans. Comp.*, **C-21**(1), 715-729.
- Stodt, R. W., and L. O. Grant, 1976: Satellite cloud climatology of summertime cumulus research areas. *Proceedings, International Conference on Cloud Physics (Boulder)*, AMS, Boston, pp. 423-427.
- Suomi, V. E., and T. H. Vonder Haar, 1969: Geosynchronous meteorological satellite. *J. Spacecraft Rockets*, **6**, 342-344.
- Woodley, W. L., J. Simpson, R. Biondini, and G. Sambataro, 1976: On NOAA's Florida Area Cumulus Experiment (FACE) main rainfall results, 1970-1975. *Proceedings of the Second WMO Scientific Conference on Weather Modification*, WMO, Geneva, pp. 151-158. •

announcements

New edition of *The International System of Units (SI)*

The revised 1977 edition of the National Bureau of Standards Special Publication 330, *The International System of Units (SI)*, is now available. This edition, like previous editions in 1971, 1972, and 1974, is the approved U.S. English translation of the International Bureau of Weights and Measures publication, *Le Système International d'Unités (SI)*, which is recognized as the most authoritative international document on the modernized metric system, commonly referred to as SI.

The 1977 edition includes a subject index, as well as several changes in the text. Its larger size, 20 × 26 cm, features titles in the margins that guide readers to topics of interest. The publication is available at a cost of \$1.60 from: Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Order as SD Catalog No. C13.10:330/4, Stock No. 003-003-01784-1.

New journal—Italian Physics Society introduces a geophysics journal

Beginning in January 1978, the Società Italiana di Fisica (Italian Physics Society) initiated a new publication devoted

to geophysics. The journal entitled, *Il Nuovo Cimento—Section C*, will publish articles in French, English, Italian, Spanish, or German. The following subjects will be covered: hydrospheric and atmospheric sciences, solid earth geophysics, aeronomy and space physics, and geophysical observational techniques. Prospective authors should submit two complete manuscripts to: Director of *Il Nuovo Cimento*, via L. degli Andalò, 40124 Bologna, Italy. For further information, write the editor or Professor Louis J. Battan, Institute of Atmospheric Physics, University of Arizona, Tucson, Ariz. 85721.

MIT short course: Design and analysis of scientific experiments

The Massachusetts Institute of Technology (MIT) will offer a two-week elementary course in Design and Analysis of Scientific Experiments, 19-30 June 1978. Applications will be made to the physical, chemical, biological, medical, engineering, and industrial sciences, and to experimentation in psychology and economics. The course will be taught by Professors Harold Freeman and Paul Berger. Further particulars may be obtained by writing to the Director of the Summer Session, Room E19-356, MIT, Cambridge, Mass. 02139.

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