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THE APPLICATION OF GEOSTATIONARY SATELLITE IMAGERY FOR DECISION-MAKING IN CONVECTIVE CLOUD SEEDING IN NORTH DAKOTA

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Abstract. A McIDAS (Man-computer Interactive Data Access System) workstation was employed to monitor the development, movement, and eventual decay of convective clouds over target areas totalling 366,000 km^2 in western North Dakota. Information relevant to cloud seeding strategies for both rainfall enhancement and hail suppression was relayed to the field meteorologists at their radar sites in near real-time, where the operational decisions were made. Both the utility and the timeliness of the information were evaluated. Shortcomings are also discussed.

1. INTRODUCTION

The seeding of convective clouds for crop-hail damage mitigation and rainfall enhancement has been ongoing in North Dakota for over a third of a century (Rose, 1986). Airborne seeding of thunderstorms with silver iodide (AgI) ice nuclei has been conducted annually since the early 1960's, when a number of small grain farmers initiated operations after suffering severe crop-hail damage in the course of several successive growing seasons. In 1976, the North Dakota Legislature created the state Atmospheric Resource Board (ARB) to coordinate and administrate cloud seeding within North Dakota. Since that time, participation in the annual North Dakota Cloud Modification Program (NDCMP) has been on a county-by-county basis. Presently five counties totalling 366,000 km^2 participate.

An evaluation of the hail suppression aspect of the NDCMP completed in 1987 yielded strong statistical suggestions of a reduction in crop-hail damage of 43.5% in the target areas (Smith et al., 1987). Using crop-hail insurance data compiled by the National Crop Insurance Services[1], the Smith et al. report employed historical regression techniqes to establish the relationship of the target to an upwind adjacent control area in extreme eastern Montana.

Seeding operations in the NDCMP are directed by meteorologists using digital C-band weather radars equipped with aircraft tracking capability. Forecasting/nowcasting support is provided by meteorological support staff from the ARB state offices in Bismarck, North Dakota. This support is largely provided in the form of facsimile and telephone transmissions of synoptic charts, upper air data, and near real-time satellite observations obtained through the McIDAS workstation. Additional NMC products are obtained through the Bismarck National Weather Service Forecast Office. The 1989 NDCMP project area is shown in Fig. 1.

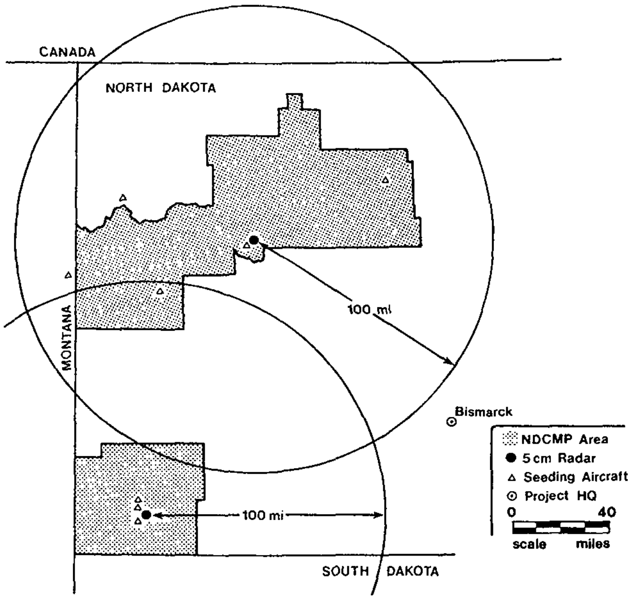

Figure 1. Operational target areas of the North Dakota Cloud Modification Project (NDCMP). Radars were located at Parshall (northern district) and Bowman (southern district).

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[1] The National Crop Insurance Services (NCIS) now includes the Crop Hail Insurance Actuarial Association (CHIAA).

Developing convective clouds having sustained updrafts and supercooled liquid water are treated with AgI or dry ice by aircraft, either near cloud base or during cloud penetration between -5 and -10°C (Boe et al., 1989a). Clouds having low natural ice concentrations are preferred. Encounters with graupel by penetrating seeding aircraft indicate that nature has already produced significant natural ice, and such clouds are usually not seeded. Radar is used to determine storm intensity, height, and for general surveillance, allowing the field meteorologists to keep aircraft advised of storm motion and propagation. The main updrafts of mature storms are avoided, as the NDCMP seeding hypothesis is based on the belief that the development of hail embryos begins in the "new growth regions" of the storms. Typically, this means that flanking lines and rain-free cloud bases are the desired target areas, while the shelf clouds that usually mark the very vigorous main updrafts are avoided (see Dennis, 1977; and Miller et al., 1975).

Since the inception of efforts to suppress hail through airborne seeding, a major difficulty has been that of responding consistently in a timely fashion to developing deep convection. Even if a developing cloud is monitored visually or with radar from its beginning, it is often impossible to get seeding aircraft to the target cloud before the hail-formation processes are well underway. Consequently, it is imperative that the short-term forecasting be the best available, so that development be anticipated as much as possible. Short-term forecasting (nowcasting) has advanced much since the advent of routine real-time satellite imagery. For example, it is now often possible to identify thunderstorm outflow boundaries upon which deep, severe convection eventually initiates, sometimes many minutes in advance of the onset of such development (Purdom, 1982).

2. THE McIDAS WORKSTATION

The McIDAS workstation is designed for animated display of satellite imagery and weather data. Capabilities include real-time access to satellite imagery and conventional synoptic data, graphic overlay of maps and synoptic data fields, animation of image or graphics frames by looping at user-selected rates, and pseudocoloring of imagery.

The workstation consists of a "tower" containing the RAM memory necessary for image storage, a high-resolution RGB monitor, a monochrome display, keyboard, joysticks, and a printer. The workstation is linked by a 9600-baud dedicated telephone line to the host mainframe computer at the Space Science Engineering Center (SSEC) at the University of Wisconsin, Madison. The SSEC mainframe computer contains the operating system, application programs, and data processing subroutines. The workstation memory allows storage of 32 image frames, and 32 graphics frames. Any graphic frame can be nondistructively overlayed on any image frame, and either the graphics or image frames may be "turned off" to allow display of one without the other.

3. DATA BASE

Images from the Geostationary Orbit Environmental Satellite, GOES, are downloaded via satellite downlink at SSEC, and subsequently stored on mainframe disc, where access by the workstation is possible. Three types of imagery were employed during the 1989 field project. These were: 1 km and 4 km resolution visual-wavelength imagery (1KM-VIS, 4KM-VIS), and 4 km resolution infrared wavelength imagery (4KM-IR). The IR channel employed was the "standard IR", which has a wavelength of 11.170 µm.

Loops comprised of from six to ten of the most recent frames of each image type were normally loaded and updated every 30 minutes. In the context of the North Dakota Thunderstorm Project (NDTP; Boe et al., 1989b), rapid scan (or RISOP) satellite data were available upon request through the National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri. Additional RISOP data were also often available whenever NSSFC or the National Severe Storms Laboratory (NSSL) initiated rapid scanning to meet their own needs. Downloading of new imagery to the workstation routinely began approximately 7 minutes after initiation of satellite scanning.

When new satellite imagery was being received no faster than every 10 min, all three loops were routinely updated as soon as the data became available. During 5 min RISOP periods, the data rate would quickly exceed the workstation's ingest capability, and one loop would not be updated. Usually the inactive loop would be the 4KM-VIS.

Each of the three image types were routinely downloaded as soon as practical after becoming available on the SSEC mainframe. Normally, new images were available every 30 min, however RISOP periods often increased imagery frequency to 15, 10, and even 5 min intervals. All images were centered just slightly west of the NDCMP operational area, to include the operational area and that immediately upwind. This representation gave the observer a view of approaching weather along with the cloud formations within the target area.

For synoptic scale overview of the development of convective systems, the 4KM-VIS imagery was most useful (Fig. 2). Propagation and movement of upwind cloud formations were easily recognized when the images were looped, i.e., viewed sequentially, thus imparting a sense of motion to the clouds. Frontal systems and the cloudiness associated with the vorticity maxima linked to rapidly moving short-wave troughs proved easy to track with 4KM-VIS imagery. This was true even when such disturbances had only diffuse cirrus associated with them; in fact the

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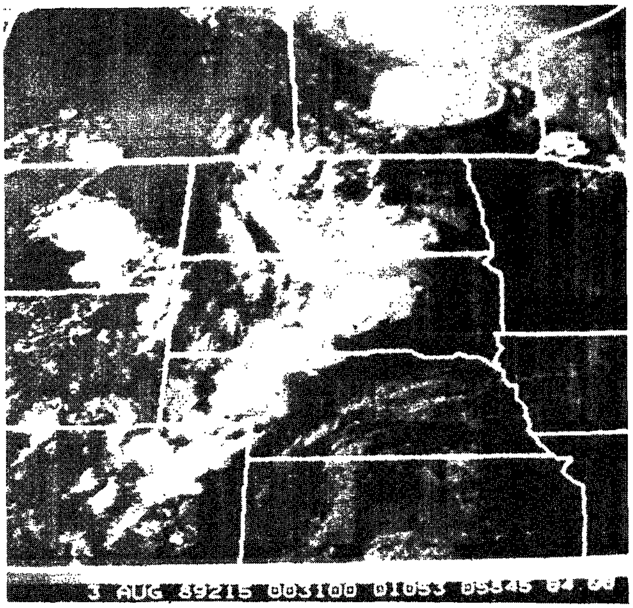

Figure 2. Visual imagery of 4 km resolution for 1930 CDT 3 August 1989. In addition to the widespread convection over the central Dakotas, a developing complex is also clearly visible in eastern Montana.

presence of such cloudiness can be used to confirm the locations of vorticity centers indicated by National Meteorological Center (NMC) products.

The 4 km-resolution infrared (4KM-IR) imagery can be pseudocolored with any user-defined color table, which greatly facilitates the task of resolving subtle temperature differences (Fig. 3). This temperature can then be used to estimate cloud top height by comparison with the temperatures and heights obtained from an appropriate nearby sounding. While only an approximation, such estimates proved useful in assessing the seeding potential of the cloud. Typically, cloud top temperatures of thunderstorms reaching the tropopause estimated via the IR imagery were a few degrees C colder than actual temperatures. This "error" is a manifestation of: (a) absorption at 11.170 µm wavelength by different constituents in the atmosphere; and (b) the fact that this wavelength, as applied by SSEC, is most accurate near the surface. Thus, the IR temperature estimates of lower (warmer) clouds were generally only 1 to 2^{o}C too cold. Ultimately, cloud top height estimates had to be adjusted downward by 0.3 to 0.5 km.

The 1 km resolution visual imagery (1KM-VIS) was found to be most useful when storms were approaching the target areas and on days when convection was initiated in the project areas and grew relatively slowly (Fig. 4). In these cases, the 4KM-VIS was initially unable to detect even fields of cumulus congestus. The higher resolution also allowed easy discernment of feeder cell lines, overshooting tops and general cell development.

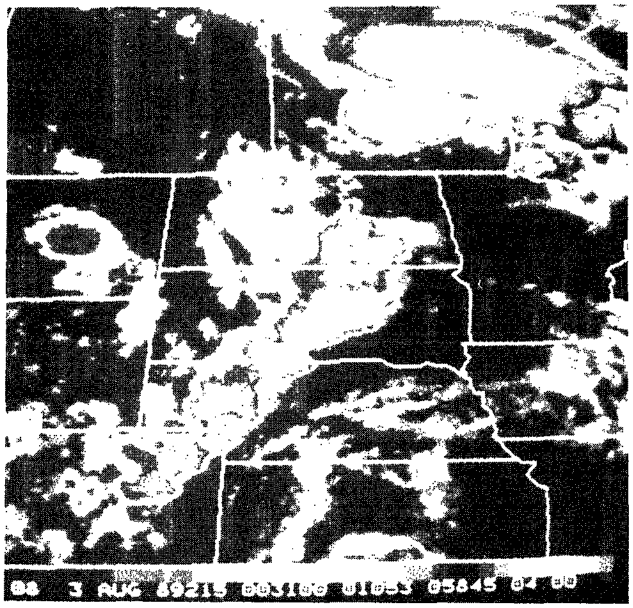

Figure 3. Infrared imagery recorded at the same time as Fig. 2. The coldest (highest) cloud tops are readily identified in this IR image, while greater detail is shown in the visual image (Fig. 2).

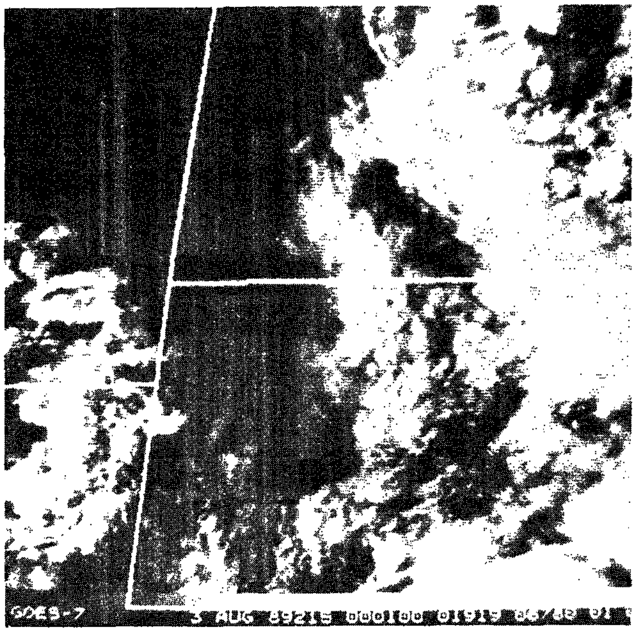

Figure 4. One kilometer resolution visual imagery recorded 0.5 h prior to that shown in Fig. 2. Individual turrets can be clearly identified in SW North Dakota and NW South Dakota.

4. APPLICATION

Real-time McIDAS/GOES satellite imagery as applied to convective cloud seeding operations in North Dakota is best discussed by objective: hail suppression (cumulonimbus), or rain enhancement (cumulus congestus). The distinctions are not actually this simple, as it appears the more significant precipitation enhancement may actually be realized in the course of hail suppression seeding (Johnson, 1985).

The seeding of supercooled cumulus congestus for rainfall enhancement is attempted by release of small amounts of dry ice (CO_2) or silver iodide (AgI) in the updraft. This seeding technique is essentially an extrapolation of the HIPLEX-1 seeding hypothesis (Smith et al., 1984), but with slightly larger, longer lived clouds. The premise is that the somewhat greater vigor and longevity of these clouds will prove sufficient for significant precipitation to result [though these clouds seldom grow larger than showers].

In general, the clouds of interest range have tops from 6 to 9 km MSL, with temperatures ranging from -10 to -20°C, though occasional warmer clouds are seeded. Horizontal dimensions are generally less than 1 km, resulting in detection problems even with the 1KM-VIS imagery. When fields of such clouds develop, they are detectable, but the response time for seeding aircraft is at least 30 minutes, so by the time such clouds are detected by satellite and the appropriate air crews are notified, the clouds most often have either produced ice naturally, sheared badly to the point of being unseedable, dissipated, or have become cumulonimbi.

Consequently, even the maximum resolution presently available has not proven to be of much use for the timely detection of cumulus congestus.

Hail suppression efforts are directed at those flanks of mature thunderstorms supporting new cloud development, i.e., flanking lines and feeder clouds. While the mature thunderstorm is easily detectable even with 4KM-VIS imagery, it is the developing flanks that are actually the targets.

While the 1KM-VIS imagery generally cannot provide adequate detection of cumulus congestus, the flanking lines so common on the south and southwest sides of mature High Plains thunderheads are readily detectable in most cases, as long as such development is not obscured by blow off from nearby storms. Prior to the demise of GOES East, it was possible to employ both GOES East and GOES West to study the same storm complexes. Because of the relatively high latitude of North Dakota, it was usually possible to "look under the anvils" at the flanking lines on the southern flanks. This was especially true of GOES West, which at that time (summer 1988) was located near the Pacific Coast, and consequently afforded a rather oblique (but pleasing) viewing angle, especially during the late afternoon hours.

Overshooting cloud tops are also readily identifiable on the visual imagery (Figs. 2 and 4). Overshooting tops mark the position of the strongest updraft, and provide substantial clues regarding the likely areas for new growth, and hence seeding. When the flanking line is obscured, the overshooting cloud tops serve notice not only that the cloud is vigorous (and consequently a hail threat), but advertise the location of the main updraft. In offering guidance to seeding aircraft, it has been fruitful to relay the locations of the overshooting tops and suggest that the aircraft check for new growth immediately to the south and southwest.

The 4KM-IR imagery is displayed with the help of a user-defined color table. The choice of colors (used in North Dakota) for the enhancement have been refined repeatedly before the present color table was derived. The authors found it desirable to have bright colors selected for the cold cloud tops, so that such cold (and therefore high) tops would attract the attention deserved (Fig. 3).

The infrared images are most useful during the actively growing phases of storm lifetimes, during which increasingly colder tops prior to anvil development, and even colder overshooting tops after, signal the development and sustained vigor, respectively (again, see Fig. 3).

Satellite imagery observations complement those of the field radars, as the signals from the latter are subject to attenuation by stronger storms. In addition, the boundary layer haze often prevalent during high-humidity periods greatly reduces visibility in the horizontal (often to 10 km or less), but satellite imagery remains essentially unaffected. In such circumstances it is possible to identify developing cumulonimbus and notify the appropriate field radar to initiate operations in a still-timely fashion.

Another aspect of satellite imagery which presently offers potential is the possibility of identifying and tracking thunderstorm outflow boundaries. It has been shown that in many areas, particularly the southeastern United States, intersections of such boundaries with each other and with other forcing features often results in explosive cloud development and very severe weather (Purdom, 1976, 1982). Such outflow boundaries are known to be active and identifiable in North Dakota as well (Klimowski and Marwitz, 1990). Efforts in 1988 and 1989 to routinely identify such outflow boundaries in North Dakota have been only marginally successful, however. It is suspected that, though such boundaries appear to serve an important role in the forcing of deep convection on the northern High Plains, they often are difficult to detect by 1KM-VIS imagery owing to the overall lower moisture content in the boundary layer. The usually drier (North Dakota) air apparently limits the development of cloud arcs such as those that often mark the positions of such boundaries in the more humid southeastern U.S.

Integrated water vapor data in the 6.7 µm wavelength have been available from the GOES satellites since the early 1980's, and hourly images have been available since 1987. While available via the McIDAS workstation, such data have not been routinely applied during the NDCMP (and are not shown here). However, a recent development suggests that such data may well have relevance to real-time interpretation of deep convection.

A narrow darkening in the water vapor channel which develops along the upstream edge of the anvils of some thunderstorms has been found emperically to be associated with severe weather (Ellrod, 1989). The darkening indicates drying, and is thought to result from blocked flow and subsidence in response to strong positive vertical velocities, i.e., strong updrafts and well organized storms.

5. SHORTCOMINGS

During nocturnal hours, only lower-resolution infrared imagery is available. When an anvil-producing cumulonimbus is thus observed, it is not possible to determine whether or not the anvil indicates the presence of an active storm, or is merely residual from earlier activity. Renewed activity beneath such anvils remains undetected unless it penetrates the anvil on a sufficiently large scale to be detected with 4 km resolution. The need for a prompt reaction to the development of significant convection has sometimes resulted in the unnecessary monitoring of moribund storms or orphan anvils. Infrared imagery assists in assessing storm vigor only when overshooting tops are clearly identifiable; lack of such features does not preclude significant activity.

Resolution of the present GOES imagery is inadequate to resolve smaller clouds, particularly those (cumulus congestus) that are often targeted for rain enhancement seeding. This is especially true of the infrared imagery.

The workstation is unable to continue loading new imagery into all three loops during periods when 5 min RISOP is sustained. Because the processing of each image takes longer than the interval between images, the system becomes overloaded. One of the three loops must be deactivated until the 5 min RISOP period ends.

Optimum application of satellite imagery might entail deployment of McIDAS workstations at the field sites. Having the workstation located elsewhere results in the field meteorologists being secondary in the information loop. The adage that "a picture is worth a thousand words" is applicable here, as availability of the imagery in the field radar would undoubtedly provide inproved perception of overall evolution of the storm systems. The initial cost and operating expenses of the McIDAS workstation presently precludes its deployment in the field; however, a new, downscaled workstation known as PC-McIDAS is now available. The PC-McIDAS has many of the capabilities of the full-scale workstation, but uses a personal computer as the heart of the display station. The possibility of deploying PC-McIDAS at the field radars is attractive, but the funding for doing so has not yet been realized.

6. CONCLUSIONS AND REMARKS

The near real-time satellite imagery obtainable through the McIDAS workstation is very helpful in promoting decreased response time via better opportunity recognition. This applies to larger clouds such as potential hailstorms, but is less applicable to smaller, isolated convection.

6.1 Rain Enhancement Operations

The imagery is usually not available with adequate time resolution to be useful for rain enhancement operations conducted on cumulus congestus. The main difficulty in such circumstances is that aircraft response time may approach an hour, while the window of opportunity may be much shorter. The response time required depends on the type of aircraft and its position relative to the target cloud. Ultimately, the authors find that most rain enhancement operations must be initiated almost exclusively in the field by first-hand visual observations of the clouds. Although the imagery obtained through the workstation is generally of little use in improving response time in rain enhancement operations, it is useful in evaluating the reaction times of field personnel in an almost real-time mode.

6.2 Hail Suppression Operations

Timely and improved decision making (nowcasting) regarding storm development and movement has been made possible by the McIDAS workstation. Project forecasters have found this to be especially true for squall lines, which typically form upwind before moving into and through the target areas.

Specifically, the satellite imagery allows and/or assists with:

a. Estimation of cloud top temperatures (and consequently cloud top heights),

b. Determination of direction and speed of movement and propagation,

c. Identification of strongest updrafts (as inferred by overshooting cloud tops),

d. Locating new growth areas, as evidenced by flanking lines and explosive cloud development,

e. Identification of outflow boundaries as marked by cloud arcs,

f. Placement of vorticity centers and jet streaks as manifested by cloudiness induced by the attendant vertical velocities, and

g. Identification of severe thunderstorms which often block flow aloft sufficiently to result in subsidence and drying in the area immediately upwind of their strongest updrafts. This subsidence is often detectable with the 6.7 µm wavelength (water vapor) imagery.

During the North Dakota Thunderstorm Project (12 June - 22 July 1989; Bismarck, ND), a terminal for the display of the data acquired by the National Lightning Detection Network operated by the State University of New York at Albany (SUNYA) was colocated with the McIDAS workstation in the project operations center. Displayed in essentially real-time were the locations, frequencies, polarities, charges transferred, and multiplicity of virtually all cloud-to-ground discharges in the contiguous United States (Orville et al., 1982). The electrical information thus available greatly complemented the satellite imagery. Advantages included the elimination of ambiguities normally associated with interpretation of infrared satellite imagery (the "orphan anvil" question), as well as improved indications of storm vigor.

Efforts have been undertaken to place such a display station in the field in future seasons, which should further increase the utility of the McIDAS workstation.

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