

AN OPERATIONAL DECISION LADDER FOR SOUTH DAKOTA

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I STRATEGY DEVELOPMENT

The term "strategy" relates to a careful plan or method and its employment to meet a goal. The goal is generally established by a user group. Strategy is generally developed by the group employed to attain the goal.

The goal of the South Dakota Weather Modification Program is to augment precipitation and decrease hail damage through the application of weather modification techniques. The application of these techniques is to be carried out under proper safeguards to supply sufficient data and accurate information in order to provide a net economic benefit and enhance knowledge concerning weather modification and to protect life, property and the public interest (South Dakota Compiled Law 38-9-3).

The 1971 South Dakota legislature established the Division of Weather Modification, a state agency, to achieve these goals. It became the task of this Division to develop the strategy.

Silver iodide was selected as the seeding agent, to be delivered to clouds by aircraft under direction of trained field meteorologists aided by weather radar. The program was not randomized due to the state's strong emphasis on achieving an economic benefit during the crop growing season. South Dakota counties participated on a voluntary basis, sharing operational costs with the state.

The Division of Weather Modification early recognized the need to develop an operational plan which would standardize the cloud seeding activities of its several remotely located field meteorologists. The strategy which was developed and written into a seven volume operations manual includes such topics as delivery modes, seeding rates, radar and aircraft operations, inter-district aircraft transfer, and opportunity recognition. As a result of suggestions received from participants at a "Workshop on Evaluation of Operational Weather Modification Programs" at the South Dakota School of Mines and Technology on March 7, 1975, the operational strategy dealing with opportunity recognition was transformed into an "Operational Decision Ladder".

II THE DECISION LADDER

A. General Comments

The decision ladder consists of several flow diagrams constructed to assist in strategy development and operational standardization. Whereas the criteria are necessarily objective, meteorologists are not discouraged from applying their judgement acquired over years of training and experience. It is unlikely that the decision ladder will be applicable to all situations.

An overall decision flow diagram is shown in Figure 1. This depicts the sequence of events comprising the strategy during a typical operational day.

Seeding rates and return times, radar calibration and operations, pilot reporting procedures, and data collection exceed the scope of this paper. They are covered in the Division of Weather Modification Operations Manual.

OVERALL FLOW DIAGRAM
(PERIODS OF ANTICIPATED WEATHER)

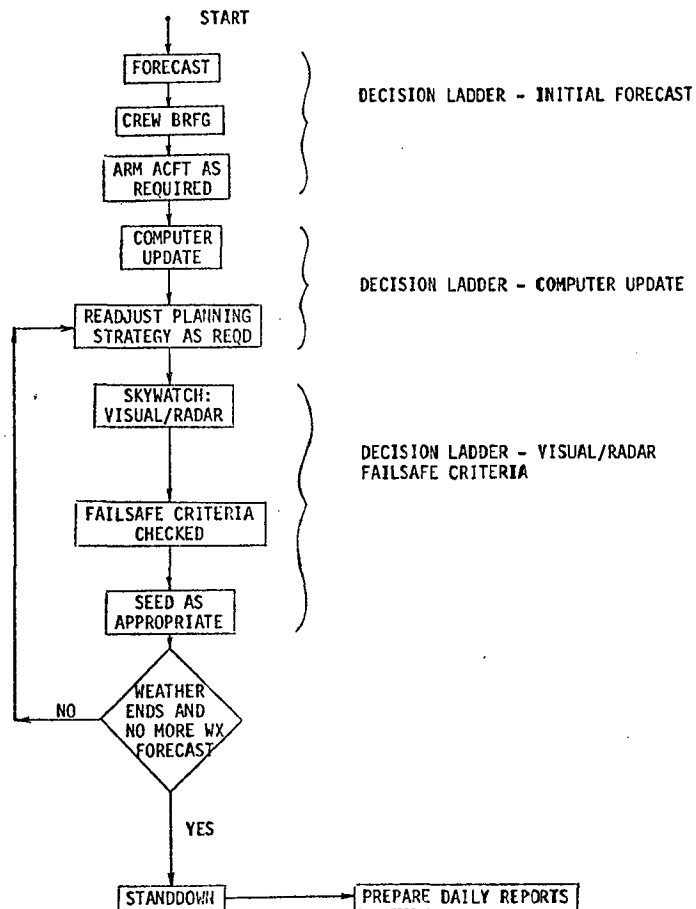


Figure 1. General flow diagram showing the components of the decision ladder.

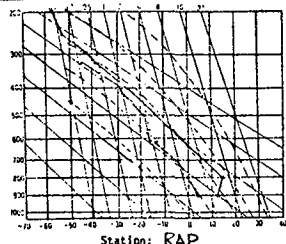
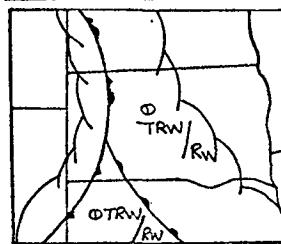
B. Initial Forecast

Forecasts tailored to weather modification operations are issued each morning at 11:00 AM during the May-August operational season. The forecasts are prepared and disseminated by a team of division forecasters employing NWS facsimile products; Service A, C, and R teletype data; synchronous meteorological satellite photographs; and time-share computer information.

The morning forecast is generally issued in two parts; an initial forecast and a computer update. The computer update is later due to delayed receipt of rawinsonde data by the time-share system.

The forecast parameters and dissemination forms were developed by Jordison (1975). Samples of the completed forms are shown in Figures 2a and 2b. Synoptic features successfully used at the Air Force Global Weather Central for severe weather forecasting (Miller, 1972) are examined daily and disseminated to the field meteorologists.

SOUNDING PARAMETERS				
	RAP	HKN	BIS	LRF
Trop Height (KFT)	36.3	38.4	37.5	37.2
Wet Bulb θ° (KFT)	11.0	09.4	08.9	11.1
500 mb Temp	-13.1 $^{\circ}$	-14.1 $^{\circ}$	-15.1 $^{\circ}$	-12.9 $^{\circ}$
-5 $^{\circ}$ C Height (KFT)	15.5	14.5	14.2	15.8
0 $^{\circ}$ C Height (KFT)	12.8	12.1	12.0	13.8
Advection Type	W / W	W / W	W / W	W / W
Lifted Index	+5.4	+9.9	+6.7	0
Total Totals	57.4	37.8	42.4	54.4
CCL (KFT)	5.8	6.0	7.7	5.2
LCL (KFT)	9.2	6.9	9.1	6.5
LFC (KFT)	NONE	NONE	NONE	NONE
T_e ($^{\circ}$ F)	+54 $^{\circ}$	+61 $^{\circ}$	+65 $^{\circ}$	+68 $^{\circ}$
T_{max} ($^{\circ}$ F)	+79 $^{\circ}$	+80 $^{\circ}$	+79 $^{\circ}$	+83 $^{\circ}$
Stable Layer (Base/Top/Th. in $^{\circ}$ C)	06.3/9.8/1.0	NONE /	NONE /	NONE /
700 mb $T-T_0$	12.0	11.0	20.0	11.0
Low-Lvl Moisture	5.2	4.9	4.4	4.5



WIND FORECAST: AFTN HIS AGES SD IN $\uparrow$ 70S & $\downarrow$ 80S. CD FRNT MOVE EWD @ 5 KTS. CD ACTVY BGVG OVR DIST 344 AFT 18Z IN TRW/RT. THIS WILL MOVE EWD DURG KTAFTN & EVNG; INTO DIST 245 BY 2200Z AND DIST 146 BY 0100Z. TRW ACCOMP'D W/ GUSTY WINDS (G-15-SKTS) AND 1/2" HAIL. TONST; CONTG ACTVTY PRMAY OVR DIST 146.

Figure 2a. Forecast Sheet #1. Includes sounding analyses, a representative sounding plot, and the forecast.

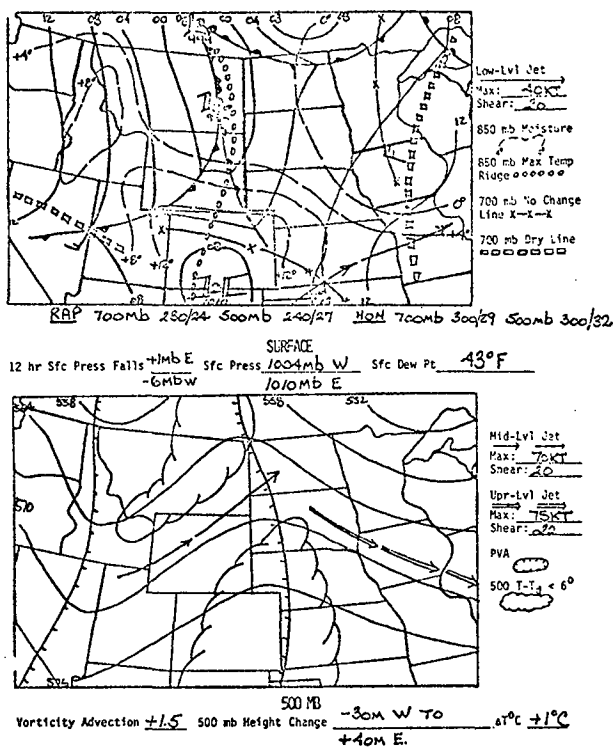


Figure 2b. Forecast Sheet #2. Graphic description of key forecast parameters (Miller, 1972).

The first item of interest to the meteorologist is the type of clouds forecast to occur in his district (Figure 3). Strategy development is quite different if stratiform rather than cumuliform clouds are expected. Stratiform clouds were not seeded during the 1975 season.

Miller's severe storm parameters are described during the briefing session. If they suggest hail or severe weather, the meteorologist is alerted to arm his aircraft for hail suppression seeding. He is also alerted to the possibility of terminating operations should weather situations develop which would lead to natural disasters (such as flash flooding or tornadoes).

Tentative indications from the North Dakota Pilot Project (NDPP) that seeding decreases rainfall on days with 500 mb temperatures below -15C led Dennis et al., (1974) to recommend that silver iodide be used very sparingly on cold days. Cumulus clouds over the northern Great Plains during cold days in April and May frequently show heavy natural glaciation. Rain stimulation is doubtful under such conditions. Clouds without natural glaciation are generally too small to produce significant rainfall even if seeded.

Stratification techniques were used to isolate similar weather days on the Rapid Project and the North Dakota Pilot Project (Dennis, et al., 1975a). Both projects showed evidence that the most favorable rain increase results

occurred on days with relatively high mixing ratios in the surface layer of air, 850 mb winds over 15 knots between 120° and 270° (clockwise), and in the absence of positive vorticity advection. Such days are typified by random convection with towering cumulus or cumulonimbus. If positive vorticity advection is present, squall lines are likely and hail suppression operations may be required.

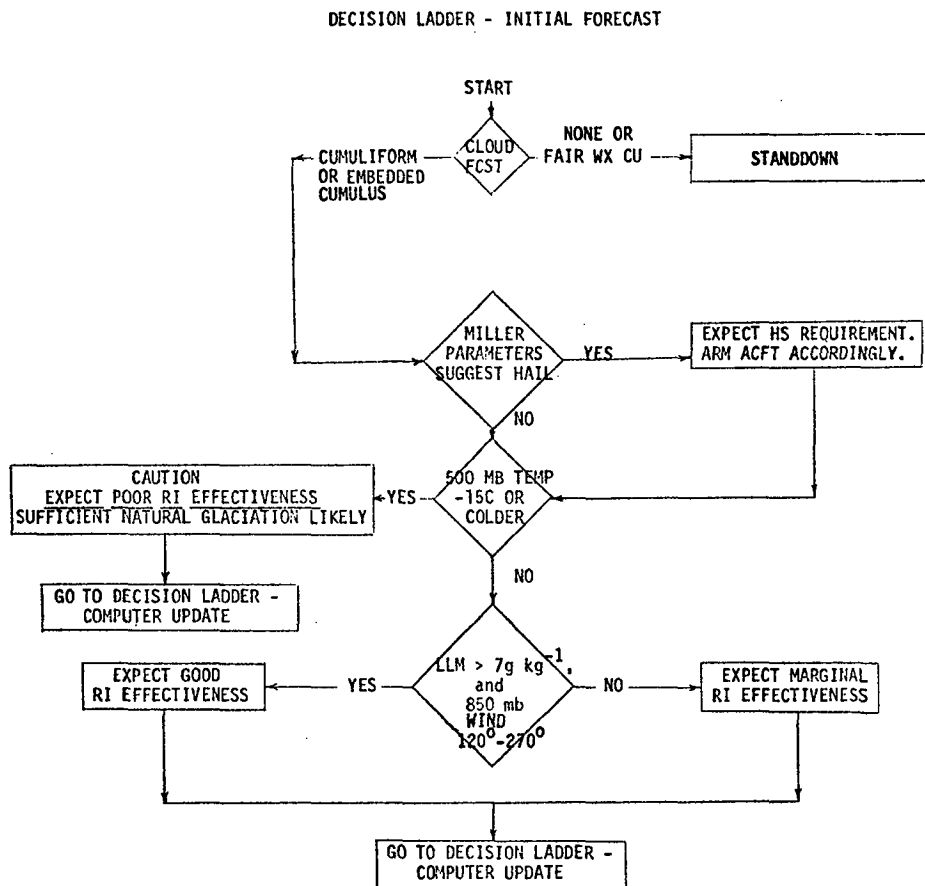


Figure 3. Flow diagram of forecast considerations.

Following transmission of the forecast and forecast briefing (via hot line telephone and telecopier), each meteorologist develops his initial strategy for the day. Specifically, he considers:

1. The type of seeding opportunity expected: rain increase, hail suppression or both.
2. Expected onset time and duration of seedable clouds.
3. The total area affected, and instantaneously covered, by seedable clouds in his target area.

4. The number of aircraft needed and those available.
5. Seeding materials needed and aircraft armament.
6. Seeding potential, hazards, and seeding cautions.

Having developed his initial strategy the meteorologist contacts his radar operators and each of his pilots. They are briefed on the current and forecast weather, expected launch time, aircraft preparations and armament, and cautions regarding seeding.

C. Computer Update

The 1200Z Rapid City and Huron, South Dakota, soundings are routinely analyzed using a steady-state, one-dimensional model of cumulus convection developed by Hirsch (1971). Soundings from North Platte, Nebraska, Bismarck, North Dakota, and Glasgow, Miles City, and Plevna, Montana, are likewise analyzed when appropriate (soundings at Miles City and Plevna were taken by the Bureau of Reclamation during the 1975 season). The sounding analysis is conducted on the Bureau of Reclamation's computer in Denver with input and output through a time-share terminal in the division's forecast office. The model used in the analysis, called the Great Plains Cloud Model (GPCM), is a 1975 version of the Hirsch Model. Pellett (1975) describes the model's use in the South Dakota program.

For rain increase decisions, the most important output of the model describes the cumulus cloud's growth response to silver iodide seeding. Cloud Catcher data (Dennis et al., 1974) emphasizes the importance of shower size in determining total rainfall production. The dynamic effects of silver iodide seeding derive from the release of latent heat of fusion as cloud droplets and rain drops are frozen. Under proper atmospheric and cloud conditions, these dynamic effects are exhibited by cloud growth.

The model simulates the artificial freezing of cloud water by converting cloud water to cloud ice at a lower level in the cloud. The conversion takes place linearly between -20C and -40C in no-seed simulations, and between -5C and -25C in seeding simulations. The accompanying latent heat release, and the resultant increase in parcel buoyancy (stimulating the updraft) are primary factors in the natural/seeded model differences. Resulting cloud top height differences are greatly dependent on the details of the environmental lapse rate.

Modeled cloud growth is described in terms of the difference in cloud top height (Δh) between seed and no-seed model runs for a given sounding and given cloud base updraft radius. By running the model for several updraft radii, the meteorologist is able to simulate the dynamic response to seeding of a rather broad field of clouds which might occur. Days on which the model predicts increases in cloud depth ($\Delta h > 0$) due to dynamic seeding and on which seedable clouds develop, promise the greatest rain increase effectiveness (Figure 4).

DECISION LADDER - COMPUTER UPDATE

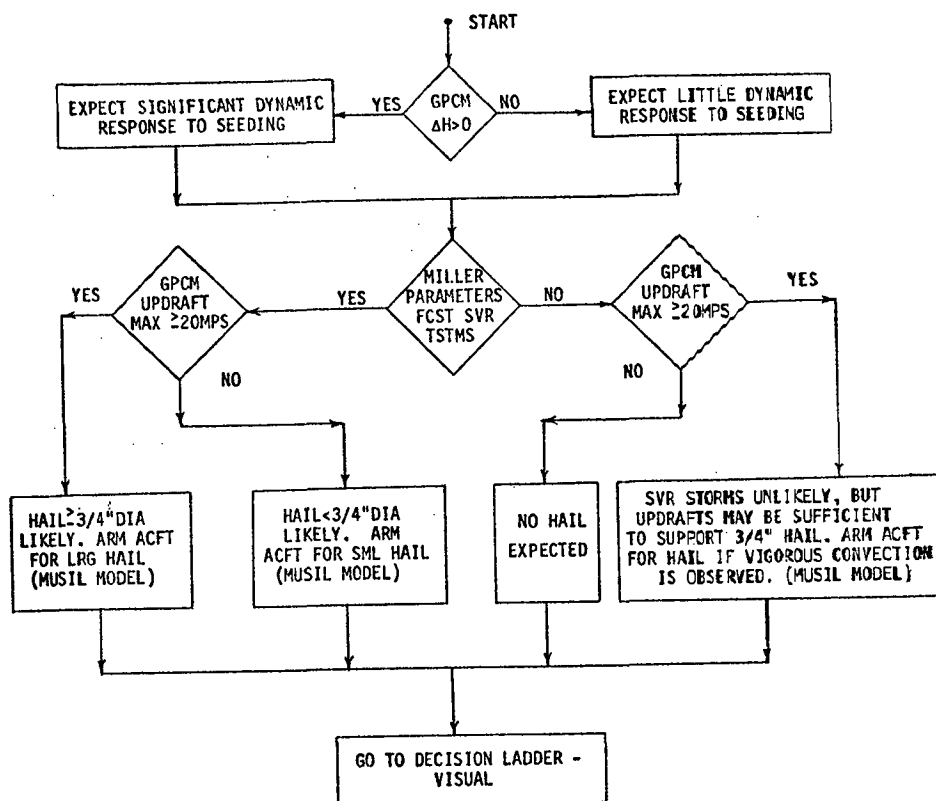


Figure 4. Flow diagram of cloud modeling considerations.

The model also provides clues as to the likelihood of damaging hail. Dennis and Musil (1973) were interested in the parameters controlling hailstone size in their one-dimensional, non-steady-state model of a growing feeder cloud. They found that the maximum in-cloud updraft speed and the temperature at which it occurs, used together, provide a reasonably good predictor of the size of hailstones likely to reach the ground. Their diagram relating these parameters is included in the South Dakota Operations Manual. In light of the low cloud temperatures at which most northern Great Plains hailstorm updrafts peak however, a 20 m sec⁻¹ peak updraft speed serves as a reasonable delineator between small and large hailstone occurrences.

As a side note, the magnitude of the model predicted maximum updraft speed provides the forecaster with a feeling for the atmospheric stability. A model predicted max updraft speed in excess of 50 m sec⁻¹ combined with a minor triggering mechanism often points to explosive thunderstorm development.

D. Skywatch: Visual

Now that the meteorologists have a mental picture of cloud development with its likely response to seeding, and have prepared their personnel and equipment to handle the anticipated weather, the field units enter the sky-watch (Figure 5) phase of operations. Meanwhile the forecasters watch for the first signs of development through satellite photographs and teletype reports.

As convection begins, meteorologists and pilots must be particularly alert to the rate of cloud development, visual signs of shear, natural glaciation, and tower cut-off due to dry air entrainment. Problems with embedded cumulus occasionally occur during the early portion of the May-August season, but are quite infrequent in the mid to late summer.

Aircraft must be launched early enough to reach the cloud at its lower threshold of seedability. This requires some anticipation of cloud development, the primary keys being forecast information and visual clues.

Clouds showing natural glaciation on days with 500 mb temperatures -15°C or colder are not seeded for rain increase. Any seeding conducted on non-glaciated clouds on such days is done very sparingly, and terminated at the first sign of glaciation in the seeded cloud.

Cloud base heights are measured through aircraft reconnaissance. Clouds with bases 12,000 feet AGL or higher are not seeded for rain increase. It is unlikely that a significant amount of any rain initiated by seeding would reach the ground before evaporating.

In the absence of cloud model runs to simulate cloud response to seeding, good results are likely by restricting seeding to those isolated cumulus clouds whose tops penetrate the -8°C level and have an unglaciated "cauliflower" appearance (Dennis *et al.*, 1974). Considering the possibility that the sounding analyzed by the model may not be representative of conditions at the time of convection, Dennis' "Rule-of-thumb" seems appropriate even with cloud model information available.

Cloud base diameter is easily measured by the pilot. Clouds with base diameters of less than 1 mile are likely either to be too shallow for the collision-coalescence process to work effectively (and top temperatures likely warmer than -8°C) or tall and skinny, with a tendency to pinch off from dry air entrainment. Such clouds should be given a chance to more fully develop before seeding.

Experience of the Institute of Atmospheric Sciences on Project Cloud Catcher and the North Dakota Pilot Project suggests that the best candidates for rain increase seeding are cumulus clouds with depths in the 8,000 to 30,000 foot range. Clouds shallower than about 8,000 feet are seldom efficient rain producers due to their relatively large surface area to volume ratios (and resultant entrainment problems). Their tops are generally too warm for effective use of silver iodide. The dynamic seeding effect seems to taper off in an undefined manner as cloud depths approach 30,000 feet. These suggestions are supported by cloud model runs showing the most significant increases in modeled cloud depth to take place for natural clouds in the 10,000 to 30,000 foot depth range (Dennis *et al.*, 1975b). Additionally, clouds with depths greater than 30,000 feet frequently have hail potential in South Dakota.

DECISION LADDER - VISUAL (GROUND & AIR)

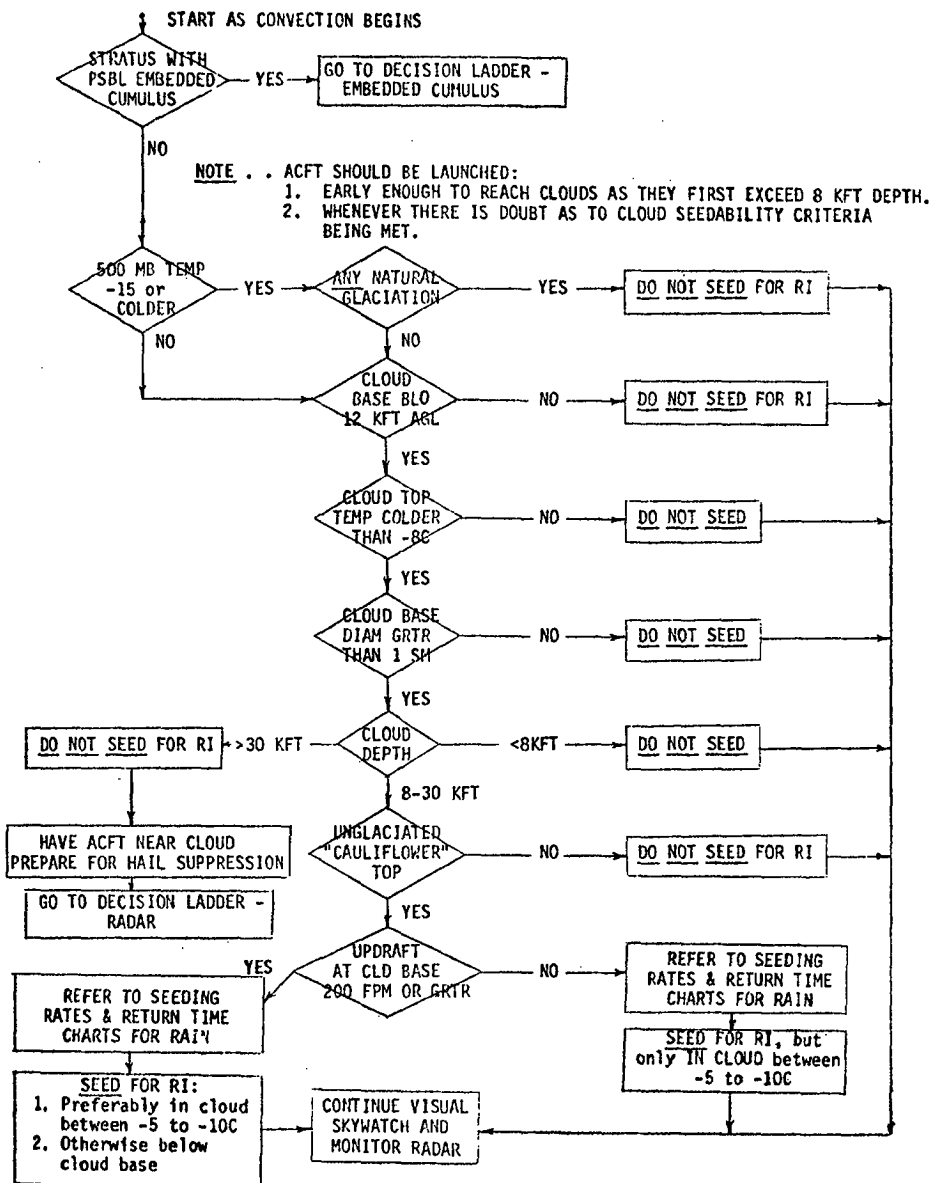


Figure 5. Flow diagram of the visual opportunity recognition process.

The cloud base updraft speed is important in two respects for rain increase decisions. It provides an indication of how vigorous the cloud is and suggests the rate at which the cloud seeding material will be carried from cloud base to the activation zone. Experience with clouds having base updrafts of less than 200 feet per minute suggests they are best seeded using small charge ejectable pyrotechnics in cloud between -5C and -10C. This provides some assurance that the seeding material will reach the supercooled cloud zone.

In conjunction with visual skywatch, the radar should be scanned for the development of echoes. Once detected, echoes and echo systems should be evaluated with the aid of the radar decision ladder and visual observations.

E. Skywatch: Radar

Radar is a rather poor tool in the initial phases of rain increase strategy. A meteorologist waiting for the development of radar echoes before initiating his rain increase operation will probably miss the earliest and best seeding opportunities. On the other hand, radar can provide useful information on shower movement, areal coverage, development, and intensification, helpful in rain increase as well as hail suppression strategy. Radar becomes increasingly important for nighttime rain increase seeding as a means of guiding aircraft to shower areas. Once there, pilot observations become an important guide to rain increase strategy. The aircraft tracking ability provided by the radar is valuable for both types of operations.

Radar surveillance should be conducted when cloud development is anticipated to occur in or adjacent to the operations area, meteorological phenomena conducive to echo production are observed visually, echoes are observed, or any time when reasonable doubt of a NO GO condition exists. In as much as the radar is most useful in analyzing the larger storms, the radar decision ladder is directed at the development of hail suppression strategy (Figure 6).

It is not a new concept that storms with echo tops penetrating the tropopause should be regarded as potentially severe. Tropopause penetration attests to the vigor of a storm. As a general rule-of-thumb, it requires about a 10 m sec^{-1} (2000 fpm) rate of parcel rise at the tropopause to achieve a 1 km penetration. Donaldson (1965) lists tropopause penetration among his suggested criteria for recognizing the development of severe storms.

Severe storm identification by radar echo intensity has also received considerable attention. Dennis *et al.*, (1971) used X-band and S-band radar to observe hailstorms in western Nebraska. They found hail threshold values of 45 dBz for X-band detected storms and 51 dBz for S-band storms with 90% detection probability (90% of the hailers studied had equivalent reflectivity factors exceeding the threshold value). In utilizing a 90% detection probability, it is understood that 10% of the actual hailers will not be correctly identified. Additionally, about 15% of the S-band and 35% of the X-band identified "hailers" will actually be non-hailers. Dennis *et al.*, (1970) studied western South Dakota hailstorms with X-band radar, finding 90% of the cases with hail having maximum reflectivity factors in excess of 42 dBz. Donaldson (1965) suggests use of X-band reflectivity factors greater than 40 dBz or S-band reflectivity factors greater than 55 dBz as indicators of severe storm development. C-band radar were used exclusively on the South Dakota Program during the 1975 season. Both X and C-band radar were used previously.

The significance of severe weather echo signatures has been well documented. Ritter (1975) summarized the work of numerous investigators in a memorandum prepared for our forecasters and field teams. The observation of hooks, line echo wave patterns, etc. alerts our operators to severe weather potential sometimes before hail threshold echo intensity criteria is met.

DECISION LADDER - RADAR

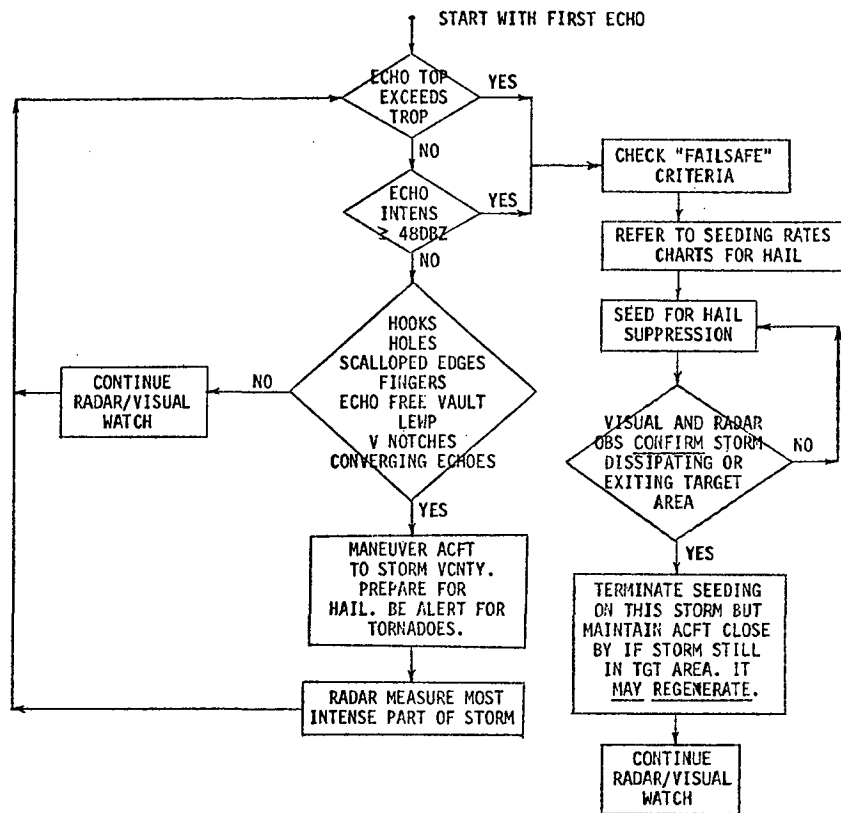


Figure 6. Flow diagram of severe weather echo recognition.

Once thunderstorms approaching hail potential are identified by radar, aircraft, and/or visual observation; "Failsafe" criteria are checked. These are considerations aimed at termination, temporary, or permanent, of seeding operations to avoid contributing to a hazardous condition. This task is particularly difficult since part of the project goal is to suppress hail. The meteorological conditions conducive to hail are frequently also apt to spawn tornadoes, flash flooding, and wind damage. For this reason, the forecasters are alert for reverse shear wind fields and stationary fronts, particularly in the Black Hills. Field crews are alert for slowly moving storms or storm systems producing high rainfall rates. Topography and soil moisture conditions are prime considerations. Pilots are instructed not to seed tornadoes and funnel bearing clouds. Seeding is not conducted on storms judged by the pilot or meteorologist to be producing excessive rainfall even if hail is also a problem.

Aircraft are kept on a severe storm, seeding or close by, until the storm is no longer a threat to the target area. Experience has shown that prematurely recalling aircraft from a hailstorm may prove disappointing.

F. Embedded Cumulus

The seeding of imbedded cumulus clouds is treated separately mainly due to the problems encountered in determining cloud seedability (Figure 7). The preferable way to attack the problem is from on top, where the pilot can visually access the seeding potential. Short charge ejectable pyrotechnics can be delivered to growing towers.

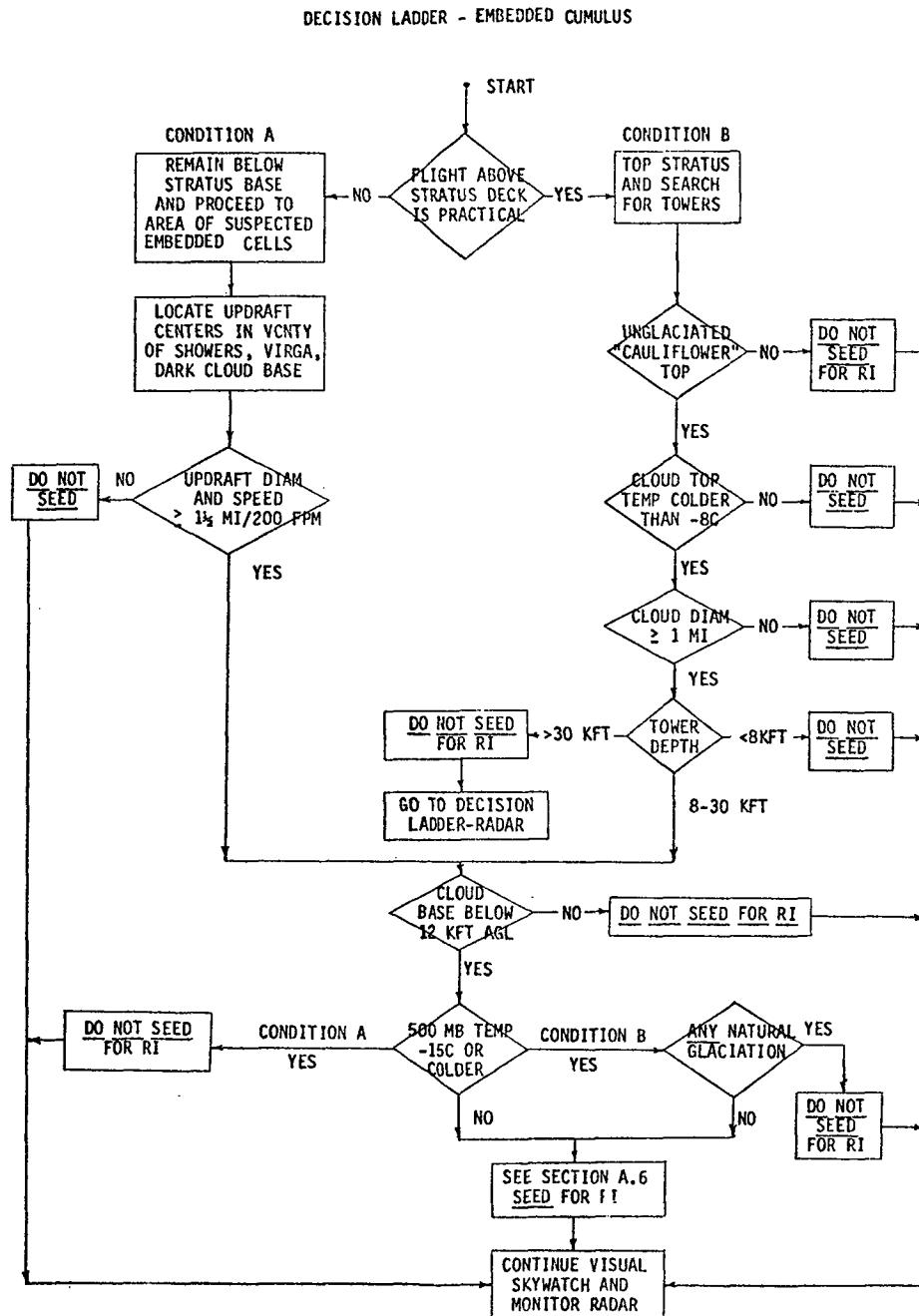


Figure 7. Flow diagram of embedded cumulus recognition and treatment procedures.

When flight above the stratus deck is impractical, the aircraft is directed to the area of suspected convection below cloud base with the assistance of radar and pilot observations. Airborne measurements of cloud base height and updraft diameter and speed as well as the 500 mb temperature become important factors in determining seedability.

III CONCLUSIONS

Assessment of a cloud or cloud system for seeding treatment suitability must include a number of factors. Decision ladders provide a convenient method of summarizing synoptic conditions, cloud model predictions, observed cloud characteristics, and radar observations in the strategy development process.

The decision ladders are necessarily based on objective criteria. They cannot possibly apply to all weather conditions encountered in the northern Great Plains summer season. They do not relieve the meteorologist of his responsibility to employ his experience in making sound operational decisions. Yet, our field meteorologists have found the decision ladders useful in their daily operations using several aircraft over millions of acres.

ACKNOWLEDGEMENTS

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