Winter Storms over the San Juan Mountains. Part III: Seeding Potential[1]

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ABSTRACT

The potential for snowfall augmentation in the San Juan Mountains of southwestern Colorado is considered. We show that the seeding criteria and delivery method used in the Colorado River Basin Pilot Project were not suited to the storm structure and characteristics described in the preceding two papers. New criteria are suggested and compared to the available statistical results. It is suggested that opportunities for precipitation enhancement by seeding occur in the latter part of the storm sequence, are associated with the release of convective instability, and can be identified by the presence of a zone of horizontal convergence upwind of the mountain range.

1. Introduction

The preceding papers in this series (Part I, Marwitz, 1980; Part II, Cooper and Saunders, 1980) discussed the observed dynamical and microphysical characteristics of some San Juan storms. In this paper, we will show that the observed storm characteristics differ from those assumed when the Colorado River Basin Pilot Project (CRBPP) began, and we will reconsider the potential for precipitation augmentation from these storms. We will also discuss the results of the statistical experiment in light of the picture of the storms which has emerged.

2. Generalized storm characteristics

This section presents some generalizations of the results from Parts I and II. The storm features are also consistent with the more extensive data set in Marwitz *et al.*[2] These are presented so that an assessment of seeding potential may be made with reference to a specific concept of the storm structure.

Fig. 1 shows a schematic time-height cross section for a typical storm and storm stages. The four storm stages are classified on the basis of convective instability in the lower cloud layer. Eleven of the 12 storms studied exhibited this same basic evolution from a stable to an unstable storm

Fig. 2 shows the airflow and the microphysical properties of the storms during the stable, neutral and unstable stages. To indicate the general regions of the storms through which precipitation particles pass before falling to the target area, calculated ice crystal trajectories are shown. For all except the steepest trajectory in each panel of Fig. 2, the ice crystals were specified to originate as 10 μm Pla crystals [following the Magono and Lee (1966) classification] and grow and fall [in accord with the equations of Davis (1974)[3]] in representative wind fields. The steepest trajectory in each panel shows the fall of an ice crystal with a terminal velocity of 1 m s^{-1}. These trajectories are particularly uncertain in the convective region of the unstable storm stage, but provide some reference in determining which storm regions might be candidates for seeding.

a. The stable stage

As shown in Fig. 1, the low-level winds during the stable stage are not toward the mountain barrier. As a result, there is little vertical displacement of the airflow over the mountain, and liquid water contents remain low (Fig. 2a). High ice crystal concentrations result from the high cloud tops and the long upwind extent of the clouds; generally, the cloud is completely glaciated except where gravity waves provide short-lived regions of low liquid water content.

From these characteristics, the stable storm stage in the San Juan mountains appears to have low potential for snowfall augmentation. There is insufficient liquid water present to support the growth of additional crystals that might be produced by seed-

[1] This research was sponsored by the Division of Atmospheric Water Resources Management (now called the Office of Atmospheric Resources Management), Bureau of Reclamation, U.S. Department of the Interior, under Contract 14-06-D-6801.

[2] Marwitz, J. D., W. A. Cooper and C. P. R. Saunders, 1976: Structure and seedability of San Juan Storms. Final Report to Bureau of Reclamation, Denver, CO, 326 pp.

[3] Davis, C., 1974: The ice-nucleating characteristics of various AgI aerosols. Ph.D. thesis, University of Wyoming, 267 pp.

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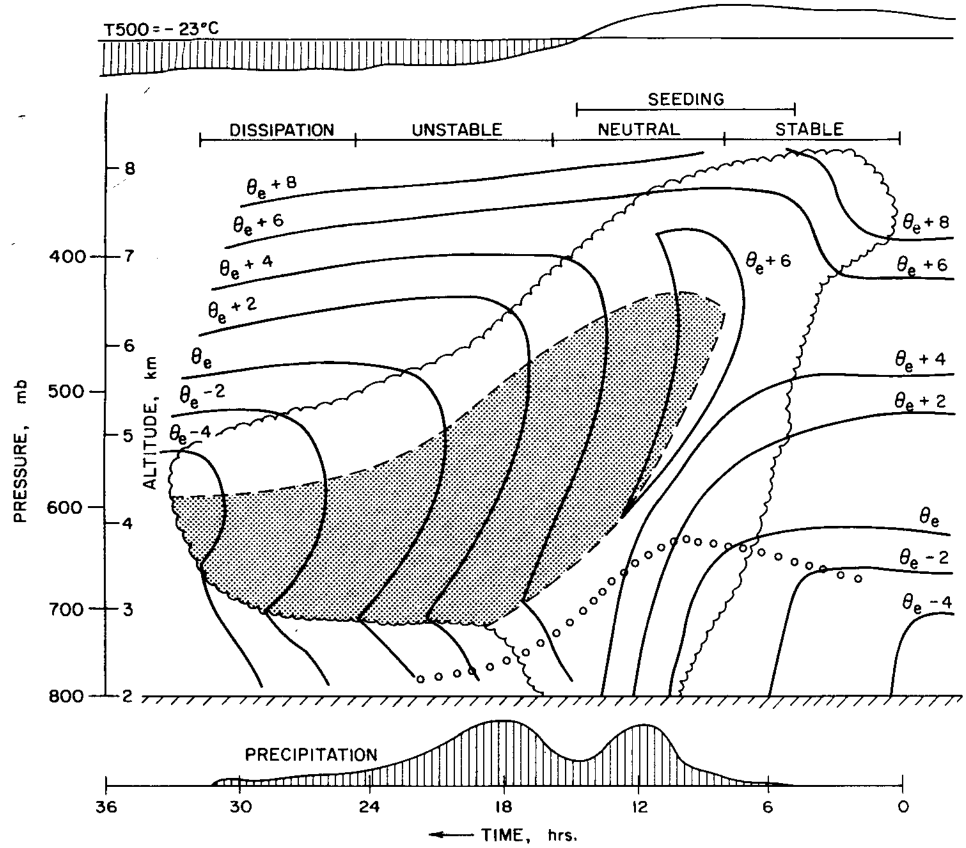

FIG. 1. Schematic height-time cross section for a typical storm over the San Juans. The solid lines are lines of constant equivalent potential temperature (θ_e), and the shaded area indicates convective instability. The typical sequence of 500 mb temperature is shown at the top. The reference baseline is −23°C. The level below which the wind directions are <160° is indicated by circles and is defined as blocked flow. The four stages of the storm and a typical seeding period are indicated.

ing, and natural ice concentrations are sufficiently high to glaciate the cloud.

b. The neutral stage

During the neutral stage significant supercooled cloud water is present in the region upwind of the target area, as indicated in Fig. 2b. Liquid water contents in this region are less than in the later unstable stage, but the trajectories shown in Fig. 2b indicate that seeding might produce precipitation in the target area.

c. The unstable stage

During the unstable stage, a convective region develops ahead of the mountains in association with a surface zone of horizontal convergence. As a result, liquid water contents are highest during this later storm stage.

To emphasize the observations upon which the generalized characteristics are based, Fig. 3 presents trajectories similar to those of Fig. 2 plotted on a vertical cross section from a specific case study. Approximate air trajectories were inferred from an equivalent potential temperature cross section with reference to the measured winds. The trajectories of the ice crystals are again approximations; they do not account for the convective region ahead of the mountains (which may provide additional vertical transport either upward or downward) and they do not account for accretional growth of the ice [although the line marked by small circles, corresponding to a fall speed of 1 m s^{-1}, gives an approximate limit to the trajectories of rimed ice crystals].

Figs. 2c and 3 show that, during unseeded conditions, the liquid water zone extends well downwind of the trajectory corresponding to a fallspeed of 1 m s^{-1}. There is thus a major part of the liquid water in regions where seeding could only produce precipitation beyond the target area. These figures also indicate that the best target for seeding is the convective region ahead of the mountains, indicated by B in Fig. 3. Part II of this series suggested that the liquid regions B and C merge together, as shown in Fig. 2c.

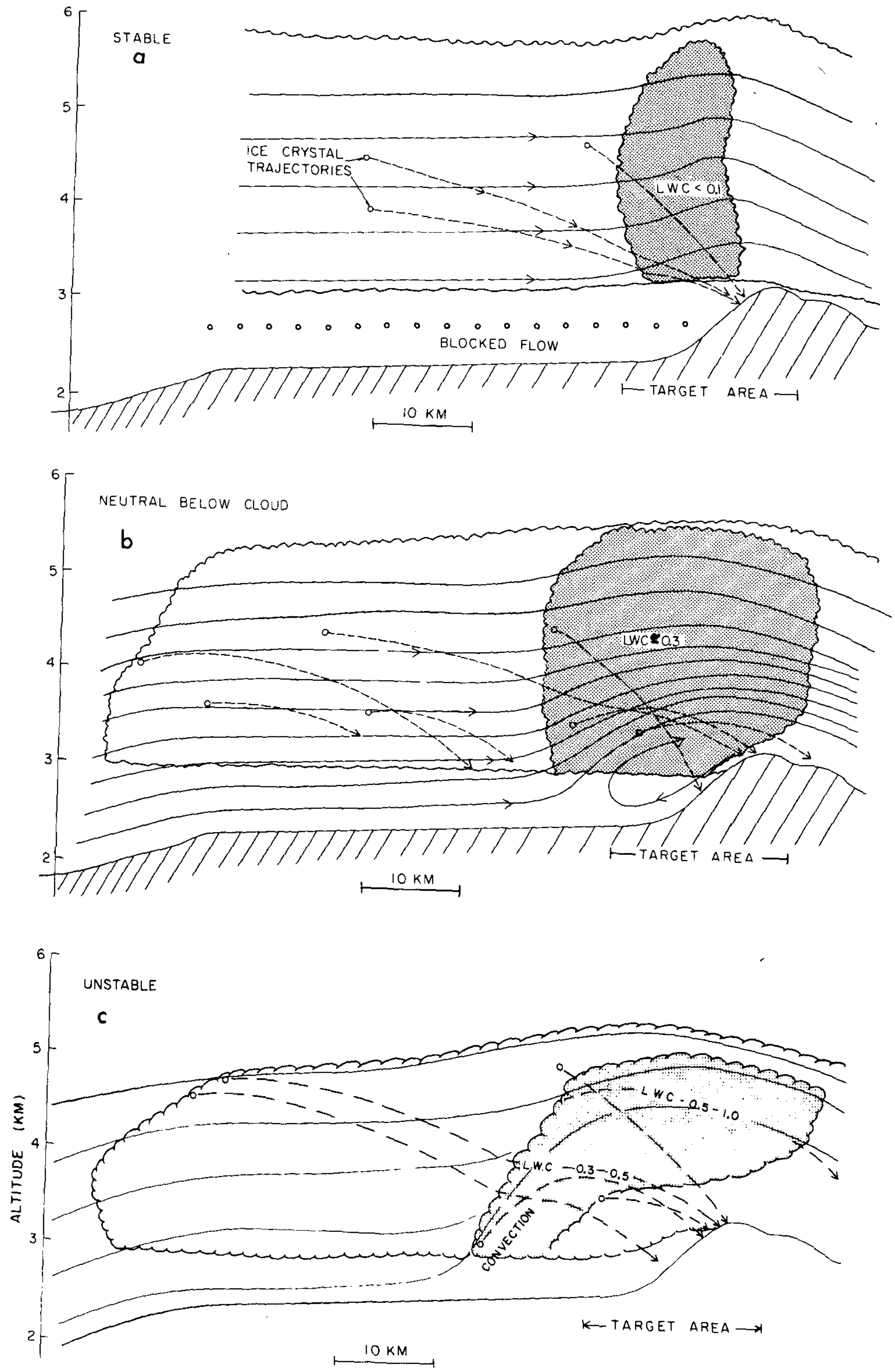

FIG. 2. Typical appearance of San Juan storms during the (a) stable, (b) neutral and (c) unstable storm stages. The airflow is from the left at ~15 m s^{-1}. The shaded regions are regions where liquid water is generally found, and some typical liquid water contents (g m^{-3}) are indicated. Solid lines with arrows show air trajectories, and the irregular lines indicate cloud boundaries. Some typical ice crystal trajectories are also shown as dashed lines. The farthest downwind trajectory shows the fall of a hydrometeor with a terminal velocity of 1 m s^{-1}.

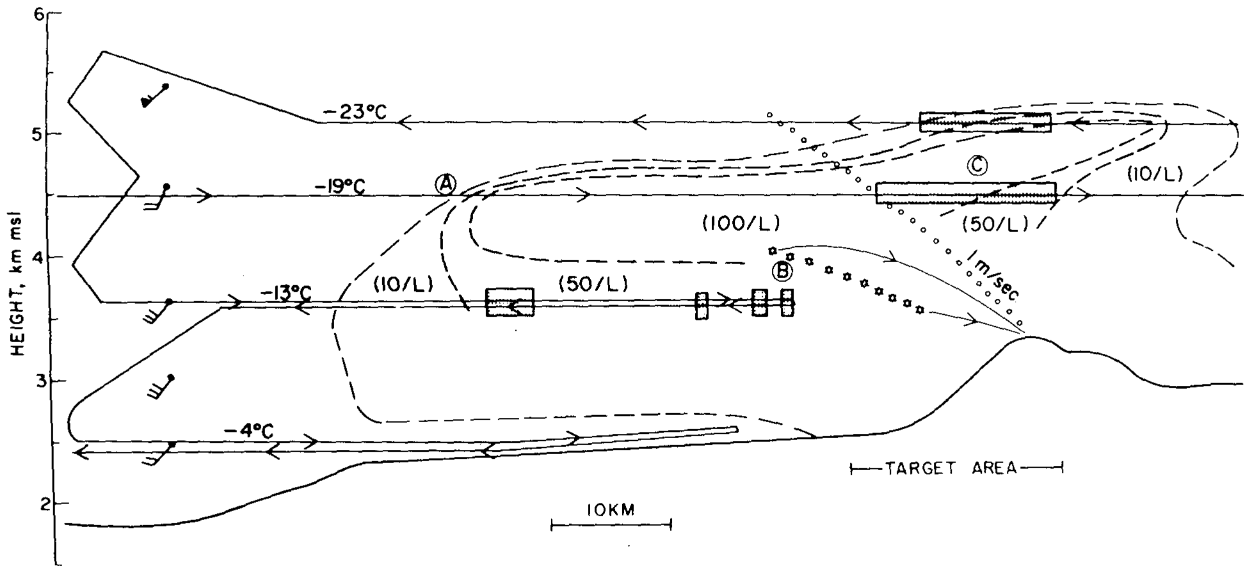

FIG. 3. Vertical cross section for a typical unstable storm stage. Shaded regions show liquid water contents > 0.1 g m^{-3}. The dashed lines are contours of ice crystal concentration. The diagram is a projection on a vertical plane oriented from southwest (left) to northeast (right). Typical ice crystal trajectories have been added as solid lines ending on the target area, as described in the text. The trajectory followed by a crystal falling at a constant 1 m s^{-1} is also shown.

The convection and the associated surface convergence zone provide mechanisms for transport of surface-released seeding material into regions of the storm where the seeding material might affect precipitation in the target area. The convective elements also frequently contained ice crystal concentrations as low as 1 L^{-1}, concentrations well below those of the regions surrounding the convective elements. The convective region thus appears to have the highest seeding potential of any region examined in these studies.

3. Examination of the seeding criteria of the CRBPP

In the CRBPP, experimental days were declared on a forecast basis. The criteria used were given in detail by Hjermstad[4] and were also discussed by Elliott *et al.* (1978). The requirements varied somewhat during the 5-year experiment, but generally included three tests covering forecast precipitation, 500 mb temperature or cloud-top temperature, and 700 mb wind direction. Seeding material was released from ground generators during periods meeting the forecast criteria.

In the context of the storm structure presented in this series of papers, some aspects of those criteria appear detrimental to the statistical experiment. Those aspects are discussed in this section.

[4] Hjermstad, L. M., 1975: Final comprehensive operations report, 1970–1975 season. Final report to Bureau of Reclamation, Denver, CO, 181 pp. [NTIS PB 250 605/1AS].

a. 500 mb temperature

Fig. 1 shows the typical variations in 500 mb temperature and in cloud top height during the storm period. As the storm developed, cold air advection in the upper regions of the storm caused the 500 mb temperature to decrease. However, advection of dry air and subsidence aloft caused the cloud tops to lower, so that cloud tops were *warmer* in later storm periods than in early storm periods. Because of this inverse relationship between cloud-top temperature and 500 mb temperature (for a particular storm), the requirement for a warm 500 mb temperature tended to exclude the later unstable storm stages from the statistical experiment and to include the early stable and neutral storm stages. Thus, in the CRBPP, the 500 mb criterion tended to exclude from the experiment the cases which, on the basis of the physical picture of Parts I and II, appear the most amenable to seeding. This criterion also tended to diminish possible seeding effects because stable cases with low seeding potential were emphasized in the selection of experimental periods.

b. Delivery of seeding material

A rotating filter sampler was used during these studies to detect the presence of the seeding material. The ice nucleus sampling technique has been discussed in Part II of this series. The ice nucleus concentrations determined from the rotating filter samples exhibited variations both from storm to storm and in different parts of a given storm. Typical

TABLE 1. Classification of storm periods.

Date	Flight	Maximum concentration (L^{-1})	AgI detected?	Prediction	CRBPP classification
29 Dec 74	1	3.1 over mtns <0.3 elsewhere	yes	seeded, carryover	unseeded
29 Dec 74	2	<0.3	no	unseeded	unseeded
29 Jan 75	1	<0.3 (4 km) <0.1 (5 km)	no	unseeded, stable	seeded
29 Jan 75	2	1.5	yes	seeded	seeded
30 Jan 75	1	<0.2	no	unseeded, stable	unseeded
30 Jan 75	2	0.2 to 0.4	no	unseeded	unseeded
17 Mar 75		<0.1	no	unseeded	unseeded
21 Mar 75		<0.1	no	seeded	seeded
22 Mar 75	1	1.6 over mtns <0.2 elsewhere	yes	seeded, carryover	unseeded
22 Mar 75	2	<0.2	no	unseeded	unseeded

concentrations measured in unseeded cases were ~0.1 L^{-1} at $-19°C$, a value approximately five times the background concentration obtained from blank filters. In regions where the seeding material should have been present, increases to ~1 L^{-1} were found. The maximum concentration detected was 3 L^{-1}.

The filter samples were used to test seed predictions. The predictions were based on the following assumptions:

(i) It was assumed that the seeding material would not reach cloud levels during periods when the atmosphere below the mountain top was stably stratified. This assumption is in accord with the deductions from the turbulence measurements (Karacostas, 1978)[5] and with the observations of Hobbs *et al.*[6]

(ii) It was assumed that neutral or unstable stages could be seeded either by release of seeding material during that stage or by carryover of seeding material released during a preceding stable storm stage.

Seed predictions[7] were constructed before the filter data were examined, and are shown in Table 1. That table also shows the maximum concentration detected on filter samples during each of the 10 flights for which filter measurements were available. Ice nucleus concentrations in excess of 0.5 L^{-1} are assumed to indicate the presence of seeding material hence the "AgI detected" column of Table 1 is obtained. Although the discrimination between high and low levels of ice nucleus concentration is not very great, the resulting "AgI detected" column is in agreement with the "prediction" in nine of the 10 cases. No explanation has been found for the exception, unless the flight path simply missed the plumes from the generators; however, most of the ground network also did not detect increases in ice nucleus concentrations during this flight.[8]

The observations based on the presence of AgI differ from the CRBPP classification in four of the 10 cases, and the prediction based on the storm characteristics differs from the CRBPP classification in three of the 10 cases. These discrepancies indicate that the original CRBPP stratification was frequently in error. The blocked surface flow that was normally present during the stable stage kept the seeding material in the target area for as much as 12 h after the generators were turned off, and the seeding material was then able to enter later storm stages that were nominally unseeded. Two of the entries of Table 1 (29 December 1974 and 22 March 1975) represent instances of contamination from this source. This persistence of the seeding material in the target area was also documented by the studies of Hobbs *et al.*,[6] and has been discussed in detail by Elliott *et al.* (1978). The subsequent misclassification of storms in the CRBPP statistical experiment would mask any real statistical effect that might have been present.

c. *Ice crystal concentrations*

Natural ice crystal concentrations were found to be 10–100 L^{-1} in most stable cases, so the natural

[5] Karacostas, T., 1978: Turbulent diffusion over mountain terrain. M.S. thesis, University of Wyoming, 116 pp.

[6] Hobbs, P. V., L. F. Radke, J. R. Fleming and D. G. Atkinson, 1975: Airborne ice nucleus and cloud microstructure measurements in natural and artificially seeded situations over the San Juan Mountains of Colorado. Research Report X, Contributions from the Cloud Physics Group, University of Washington, 89 pp.

[7] The CRBPP classification of a storm period as seeded indicates that the seeding material should be present somewhere in the storm, not necessarily in regions where seeding could affect the precipitation. For example, the criteria predict that the 29 December 1974 case was studied during a seeded period, but seeding material on that flight was only found at low levels over the mountains; only background concentrations were found in the upwind region where the high ice concentrations originated.

[8] Hartzell, C. L. and L. W. Crow, 1976: Colorado River Basin Pilot Project, *WSSI Final Report*. U.S. Bureau of Reclamation, Denver, CO, 325 pp. [NTIS PB 254 624/OGI].

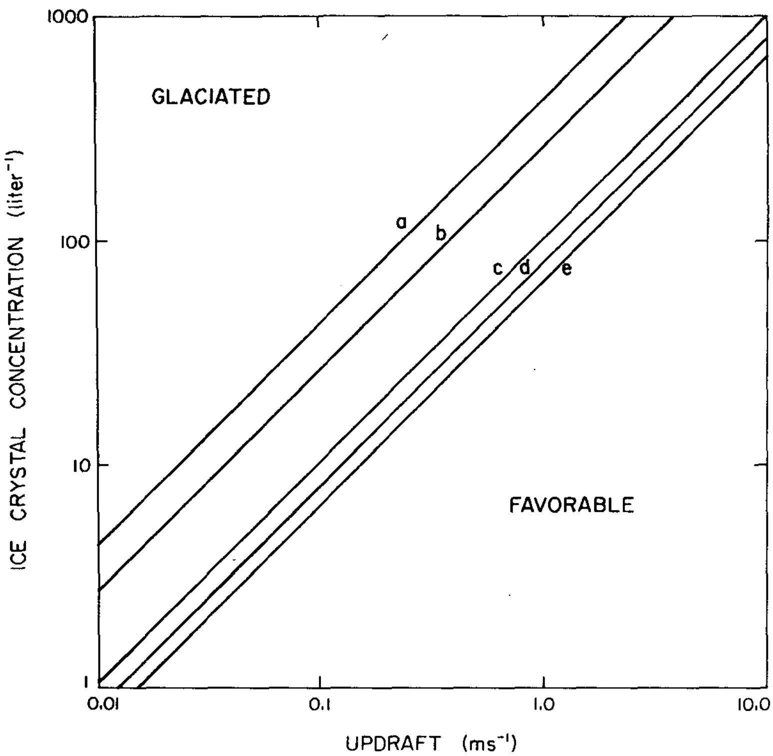

FIG. 4. Ice crystal concentration which, growing at water saturation, is able to deplete water vapor at the same rate at which the saturation vapor pressure decreases in the indicated updraft. All calculations are at 700 mb (although the results depend only weakly on the pressure) and are based on the growth rates of Ryan *et al.* (1976). The temperature and ice habit for the different lines are: (a) $T = -5$°C, 500 μm needles; (b) $T = -15$°C, 300 μm stellars; (c) $T = -10$°C, 600 μm thick plates; (d) $T = -15$°C, 1000 μm stellars; (e) $T = -20$°C, 1000 μm thick plates.

ice concentrations were as high or higher than the concentrations that were the goal of seeding. These observations raise the possibility that, in the stable case, the natural ice may be sufficient to precipitate the available moisture, and that no seeding potential exists. They further suggest that, even if a seeding potential exists, seeding must produce concentrations comparable to these natural concentrations to have a significant effect.

To investigate the ice concentrations required to glaciate the clouds, Fig. 4 was constructed. The ice crystal concentration is plotted which will convert water vapor to ice (in a water-saturated cloud) at the same rate that condensate is supplied by adiabatic ascent. For ice crystal concentrations above the plotted lines, the cloud will remain glaciated. For ice crystal concentrations below the lines, the rate of condensation exceeds the depletion rate and a supercooled cloud will form.

Fig. 4 illustrates that, in the stable stage with weak updrafts, the natural ice crystal concentrations (10–100 L^{-1}) are adequate to glaciate the clouds. Little seeding potential exists. However, in the unstable, and particularly in the convective regions upwind of the mountains, updrafts were commonly 1 m s^{-1} or greater and ice crystal concentrations were $\leqslant 10$ L^{-1}. Fig. 4 indicates that supercooled water should form in such regions, as was observed, and that it might be possible to increase precipitation by seeding there.

4. Evidence from the statistical evaluations

According to the preceding discussions, the different storm stages should be characterized by different seeding potentials. In this section, we consider if the detailed statistical evaluations which have been reported for the CRBPP support or refute this difference in seeding potential.

Elliott *et al.* (1978) and Elliott *et al.*[9] reported that the precipitation on seeded days did not differ significantly from that on control days. They attributed this result primarily to operational problems associated with the inability to forecast storm conditions

[9] Elliott, R. D., R. W. Shaffer, A. Court and J. F. Hannaford, 1976: Colorado River Basin Pilot Project Comprehensive Evaluation Report. Aerometric Research, Inc., Rep. ARI-76-1 to U.S. Dept. of Interior. [NTIS PB 262 057/3ST].

(such as cloud-top temperature) with sufficient accuracy. In addition, they reported *a posteriori* stratifications which generally supported the design criteria for the CRBPP. They found evidence for increases attributable to seeding in cases with relatively warm cloud tops (−9 to −29°C), but they found no increase in cases of strong instability.

Their report that instability was not associated with positive seeding effects appears to conflict with our view that the highest seeding potential is present in the unstable storm stages. This conflict arises because Elliott *et al.*[9] have characterized stability using criteria different from ours. The present papers have characterized storm stages as unstable if there was *convective* instability and if the airflow was appropriate to release this instability. Elliott *et al.*[9] have used *latent conditional* instability (based on the lifting of a surface air parcel) to characterize the storm periods, and they did not consider the airflow. A good example of the difference may be seen in the soundings presented in Part II of this series. Fig. 1 of Part II shows the sounding from an early storm stage, when the storm characteristics (smooth airflow, relative absence of rapid fluctuations in state parameters, unrimed precipitation, absence of high liquid water regions, etc.) indicated a stable system. There is strong latent conditional instability in this sounding, and it would fall into the unstable category of Elliott *et al.*[9] but the low-level wind was not toward the barrier so the latent instability was not released.

The difference between our characterization of stability and Elliott's is further illustrated by his statement that high instability was characteristic of early storm periods. Fig. 1 shows that the early storm periods were not characterized by convective instability, and both this figure and Fig. 7 of Elliott *et al.* (1978) show that the low-level winds in the early stages are not directed toward the mountains. The instability in early stages is conditional instability, resulting from mid-level cold air advection over a pooled warm air mass. Since the wind in this lower air mass is not upslope and since the attendant cloudiness prevents surface heating, the conditional instability does not result in convection. When convection appears in the later storm stages, it is frequently embedded convection and is associated with convective instability such as appears in the 720–770 mb layer of Fig. 6 (Part II). The stratification results of Elliott *et al.* (1978) thus are not a test of our predictions.

Their finding that cases with cold cloud top temperature have a low seeding potential may also reflect, in part, the tendency of the early stable stage to have cold cloud tops. The storms normally begin as deep synoptic-scale systems, and the coldest cloud tops occur in the early storm stage.[10] The low seeding potential of cases with cold cloud tops is thus consistent with our prediction that the early storm stages are poor candidates for seeding.

Hjermstad[4] also evaluated *a posteriori* the seed: control precipitation ratios for various storm categories, classified according to the soundings taken upwind of the mountain range. The storm category which responded most favorably to seeding was his "orographic, stable-lid, no higher clouds" category. His evaluation indicated that both warm-top and cold-top clouds in this category responded favorably to seeding. His description of this cloud category is similar to our unstable storm stage. The unstable stage was primarily orographic in character, and was generally capped by a stable layer resulting from post-frontal subsidence which also prevented any higher clouds. On the other hand, when Hjermstad considered similar storms which had mid- or high-level clouds present (as was characteristic of the early stable or neutral storm stages), the seed: control ratio was close to unity. For Hjermstad's "deep storm clouds" (which probably correspond best to our stable storm stage), the seed:control ratio was slightly less than unity. We find no conflict between his results and ours.

Vardiman and Moore (1978) examined the statistical results from seven wintertime seeding experiments, including the CRBPP. They found the most significant statistical effects to be associated with moderate instability, but they found decreases in cases of strong instability. Because they also used conditional rather than convective instability to characterize the storms, their results do not necessarily verify our predictions.

It appears that there are no direct inconsistencies between the predictions of this paper and the statistical evidence, but that the predictions are not well tested. In particular, the stratifications based on instability that have been reported do not constitute a test of the suggestions of this paper because they are not based on convective instability.

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[10] Elliott *et al.* (1978) have also pointed out the tendency for the later storm stages to have lower and hence warmer cloud tops. Elliott *et al.* (1978) probably estimated the cloud-top temperature to be colder than the true cloud top in stable stages, however, since they calculated a cloud-top temperature by lifting the cloud top indicated by the upwind sounding to a colder temperature over the mountains. We found little vertical deflection of the airflow in the stable stages, so their procedure yields cloud-top temperatures that are too cold. It is furthermore difficult to justify characterizing the seeding potential by cloud top temperature over the mountains. Fig. 2 of this paper shows that ice produced at cloud top over the mountains can have little effect on precipitation in the target area. The observed cloud top temperature over the upwind valley would probably be a better measure of the coldest ice-nucleation temperature able to affect the precipitation.

5. Identification of periods with seeding potential

Both the physical observations and the stratifications of the statistical results have indicated that there is potential for precipitation enhancement in San Juan storms. However, to realize that potential, the opportunities must be recognized and exploited in an operational program. The importance of the ability to recognize periods with seeding potential was emphasized by Elliott *et al.* (1978), who attributed the null result of the CRBPP statistical experiment to the errors involved in forecasting storm characteristics. Since these errors would be likely to occur again if similar seeding criteria were used, we have proposed some new ways of recognizing periods with seeding potential.

This paper has suggested that the unstable stage is the best candidate for seeding. That storm stage has the highest liquid water content, and has regions (associated with convection) where ice concentrations are relatively low. Further production of ice crystals in these convective regions should be beneficial.

Furthermore, this storm stage could be identified in an operational program. It is relatively easy to detect the convective instability from upwind soundings. The development of a horizontal convergence zone upwind of the mountains would be an additional indication that the storm was entering an unstable stage.

The CRBPP, as designed, produced a null result. However, evidence in this series of papers indicates that a seeding potential exists in San Juan storms. These papers have suggested new ways of characterizing the seeding potential of storms of this area, and statistical investigation of these suggestions with existing data appears warranted. In particular, stratification of the results according to a measure of convective instability, according to the existence of a surface convergence zone upwind of the mountains, and according to the time from the start of the storm period would provide statistical tests of the suggestions of these papers.

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