"REVIEWED"

GENERAL AND SPECIAL HYPOTHESES FOR WINTER OROGRAPHIC CLOUD SEEDING

C. J. Todd and W. E. Howell

Department of the Interior
Water and Power Resources Service
Office of Atmospheric Resources Management

I. INTRODUCTION

Our purpose is to improve the rate at which evidence of the effect of cloud seeding under various weather conditions can be compiled. To do this, we have used the compiled data on individual experimental events for six winter orographic cloud-seeding experiments, and we have constructed a scheme based on our understanding of physical principles of precipitation that leads, for each event, to an expectation of its outcome for seeded and unseeded conditions respectively. Matching of the varying expectations to diverse outcomes is expected to accumulate evidence faster than if expectations are undifferentiated.

The construct of physical principles constitutes what we call a general hypothesis. It is a tentative statement of how we think ice-nuclei cloud seeding works under the range of weather conditions encompassed in our data set. For each specific experimental event, the input data operate on the general hypothesis to convert it into a special hypothesis, a specific statement of expected outcome for the seeded, respectively unseeded, conditions of that particular event.

The expected outcome of seeding is under some weather conditions an increase in precipitation, under other conditions a decrease, and sometimes no change. We will have succeeded in our aim if the special expectations track the direction and magnitude of the seeding effect more closely than a less particularized hypothesis could do. At this point, we leave it as an exercise for the statistician to convert the improved expectations into an improved protocol for testing the general hypothesis and its special subsets.

The Physical Construct

Our physical construct is not ideal. It has evolved from a give-and-take between theories of precipitation and the observational data. The theories suggest certain observable parameters, and certain combinations of them, that may be superior as estimator (predictor) variables and response variables. We have made empirical choices among these variables based on their availability and reliability in the data sets and their usefulness in distinguishing between actual seeded and unseeded events.

We postulate an expectation, based on modeling studies in the following way:

> Natural precipitation will be most efficient when the cloud is rich in condensed water and has adequate time for growth and fall of precipitation particles, namely when the cloud base is relatively warm and moist, clouds are deep, and relative stability permits gradual rise of the air without the dilution and rapid ascent that accompany unstable overturning.
>
> Precipitation will be least efficient when the cloud is poor in condensed water or has inadequate time for growth and fall of precipitation particles, namely when cloud base is relatively cool, clouds are shallow, and instability shortens times of rise and causes the ascending air to be diluted with admixed drier air.

For now, we have chosen to neglect dynamic effects related to release of latent heat caused by seeding.

This postulation is illustrated in Figure 1. The depth of the cloud is represented by the temperature of its top after lifting over the mountain crest. In the lower left part of the diagram the combination of temperature and mixing ratio corresponds to unsaturated air, and no cloud forms; the surface bounding it corresponds to the physical cloud base. For some distance above the cloud base there is a region where the cloud is too shallow, too ephemeral, or has too little condensed moisture (or a combination of these) for significant precipitation to form. There is also a region (right rear) where the cloud is so wet and so lasting that, given sufficient depth, natural precipitation nearly always falls. The dotted lines running between the dry-unstable and moist-stable corners cross the gradient from low to high precipitation efficiency nearly at right angles.

A postulated effect of ice-nucleus seeding is expected to be greatest in the region of strongest gradient between naturally high and low precipitation efficiencies. This is where time is critical to precipitation process, and where seeding may affect it, under some conditions for the better (furnishing more or better embryos), under others for the worse ("freezing up" the precipitation process). No effect is to be expected when the cloud-top temperature is warmer than about -2° C. Increased precipitation is expected where the main effect of the seeding is to overcome a natural deficiency of time available, regardless of whether the subsequent growth of precipitation is by deposition or by accretion. This gain is expected to be greatest when the lifted cloud-top temperature is in the range from -5 to -30° C and the cloud layer is relatively stable. Diminished precipitation is expected where overseeding may occur, creating ice particles too small to fall or of an inappropriate habit to aggregate into clusters that would fall effectively. This loss is expected to show up when the cloud-top temperature is colder than -30° C, especially when the cloud layer is

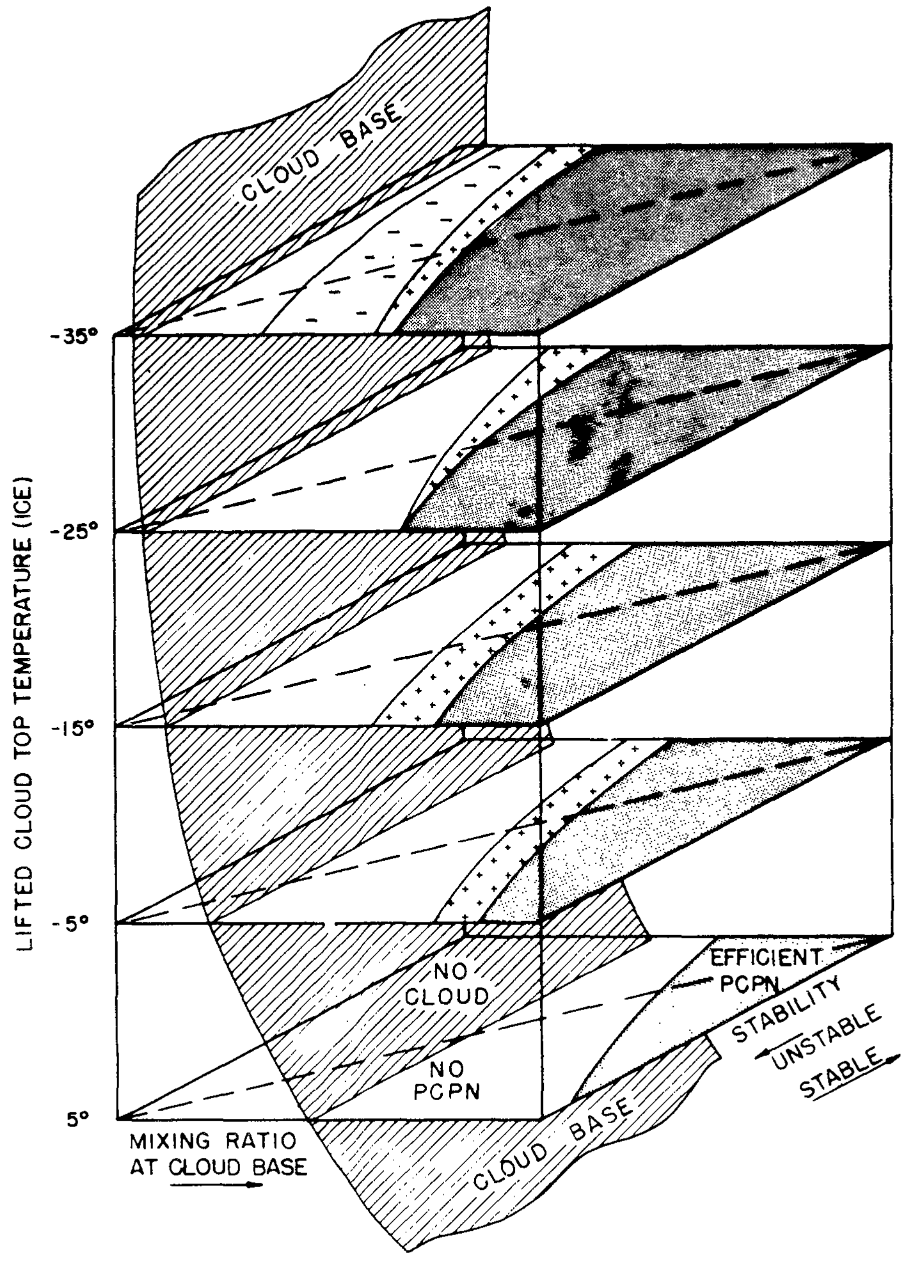

Figure 1. Postulated relationship between efficiency of precipitation and the three estimator indices, lifted cloud-top temperature, cloud-base mixing ratio, and stability. The dashed diagonal from dry-unstable to moist-unstable becomes the axis of abscissa of the (CBWS-E) index for Figure 2.

unstable enough to bring precipitation embryos to the overseed zone before they have had time to grow large enough to achieve effective fall speeds.

On the basis of these postulates, we chose three independent estimator variables and one response variable. The estimator variables are:

> BTI (Barrier trajectory index), as defined and used by Vardiman and Moore (1978) (hereafter referred to as V-M). This variable is intended to distinguish between occasions when transit time of a cloud parcel from passage over the seeding generator to passage over the orographic crest is too short to expect seeding-initiated precipitation to form and fall out onto the target, and occasions when this time is long enough for fall-out to be expected. It is the time in seconds that a snow crystal takes to travel with the 70-kPa wind (derived from rawinsonde observations) from the average seeding location to the orographic crest less the time it takes to fall at 0.5 m/s from the cloud top to the crest elevation. V-M expressed the expectation that a seeding-produced snowflake would fall upwind of the crest when BTI was less than zero and downwind (or be lost to evaporation) when BTI was greater than zero.
>
> CBWS-E (index related to moisture availability, dilution, and ascent rate). This is the sum of the saturation mixing ration in g/kg at the water-saturated cloud base and the EPOS and ENEG areas calculated from rawinsonde observations, as defined by V-M. The units are J/kg x 10^{-2} and ENEG is taken negatively. The CBWS term expresses the upper limit of liquid water possible in the cloud by condensation. The E term corresponds in an empirical manner to a double effect of convection; diluting the cloud by admixture of drier air during unstable ascent; and shortening of the time available for growth of precipitation particles before a temperature is reached where complete freeze-up occurs and growth stops. In combination, they are intended to represent a portion of the time term and moisture availability for precipitation.
>
> LCTTI (lifted cloud-top temperature for ice). As defined and used by V-M, this is the temperature derived from the rawinsonde sounding by simulating the lifting of air by the height of the orographic barrier and then noting the highest point in the main moist layer where saturation with respect to ice occurs. It is intended to represent the lowest temperature available in the orographic cloud for nucleation of ice crystals. When used in conjunction with CBWS-E, it helps complete the precipitation formation time concept. Stratification on LCTTI by V-M indicated that most of the seeding-associated precipitation decrease for the entire set was accounted for by the subset LCTTI colder than -30°C.

Our dependent (estimated, predictand) variable is: PCPN/CBWSxt. This is the ratio of the precipitation rate on the target to the moisture quantity available at cloud base. It is intended to be an index of the efficiency of conversion of condensed moisture to precipitation on the target. The target for each area is the crest group of precipitation gages as given by V-M.

Conspicuously missing from this construct are mass-flow terms describing the quantity of moisture carried across the barrier. We made many attempts to improve on the CBWS-E and PCPN/(CBWSxτ) terms by incorporating such terms as windspeed normal to the crest, but without notable success. This topic will be the subject of later comment.

II. THE DATA SET AND SUBSETS

The data set we have analyzed was drawn from six winter-orographic cloud-seeding experiments conducted in the Western United States between 1960 and 1976. These are shown in Table 1.

Table 1. - List of projects

Project	Site	Seeding operations
Bridger Range Project (BGR)	Rocky Mountains Montana	1969-70 to 1971-72 (3 seasons)
Climax Project (CMX)	Rocky Mountains Colorado	1960-61 to 1969-70 (10 seasons)
Colorado River Basin Pilot Project (CRB)	Rocky Mountains Colorado	1970-71 to 1974-75 (5 seasons)
Central Sierra Research Experiment (CSR)	Sierra Nevada California	1968-69 to 1972-73 (5 seasons)
Jemez Mountains Project (JMZ)	Rocky Mountains New Mexico	1968-69 to 1971-72 (4 seasons)
Pyramid Lake Pilot Project (PYR)	Sierra Nevada California/Nevada	1972-73 to 1974-75 (3 seasons)

This data set is identical with the one that formed that basis of the report by V-M with the exception that the Climax set was restricted to the originally designated experimental days.

After many categorizations and subsets of the data had been examined, the analysis was reduced to two categories of BTI, ($BTI < 0$ and $0 < BTI$), three categories of CBWS-E (<7, 7 to 12, >12) and five categories of LCTTI each 10° C wide and centered at 5, -5, -15, -25, and -35° C.

III. RESULTS

Figures 2a and 2b show the median seeded and unseeded values of the response variable (PCPN/CBWSxt) as a dependent variable plotted in the x-direction, for BTI less than and greater than zero respectively. In this figure, the near side combines the categories of CBWS-E less than 7, the middle plane combines categories 7 through 12, and the far side represents categories greater than 12. The number of seeded and unseeded cases is written near the corresponding points. In parentheses are entered the probabilities that the seed-nonseed differences would occur by chance, calculated by a Wilcoxon one-tailed test. These probabilities are shown only to illustrate the relative strengths of the departures and not in support of any pre-stated hypothesis.

We interpret the steady increase in precipitation efficiency with decreasing LCTTI to be related to the depth and strength of the storm system. Strong, active storms have deeper cloud systems with colder tops and are in general much more efficient producers of precipitation than shallower, weaker storms. This relationship holds true in general for both seeded and nonseeded conditions.

The vertical plane nearest the viewer (CBWS less than 7) shows that the precipitation efficiency index is small when available moisture is small or is depleted as a consequence of instability. The increase with seeding is also greatly weakened in this circumstance and becomes negative for the coldest category, strongly so in the blow-over case when BTI is less than zero. The farthest vertical plane (CBWS-E greater than 12) contained very few events and suggested no effect of seeding.

For nonseeded precipitation cases, there is a consistent but minor difference between the two BTI categories. However, seeding appears to increase precipitation efficiency much more when BTI is less than zero except under the coldest, driest conditions. We will return to this topic in the discussions.

"REVIEWED"

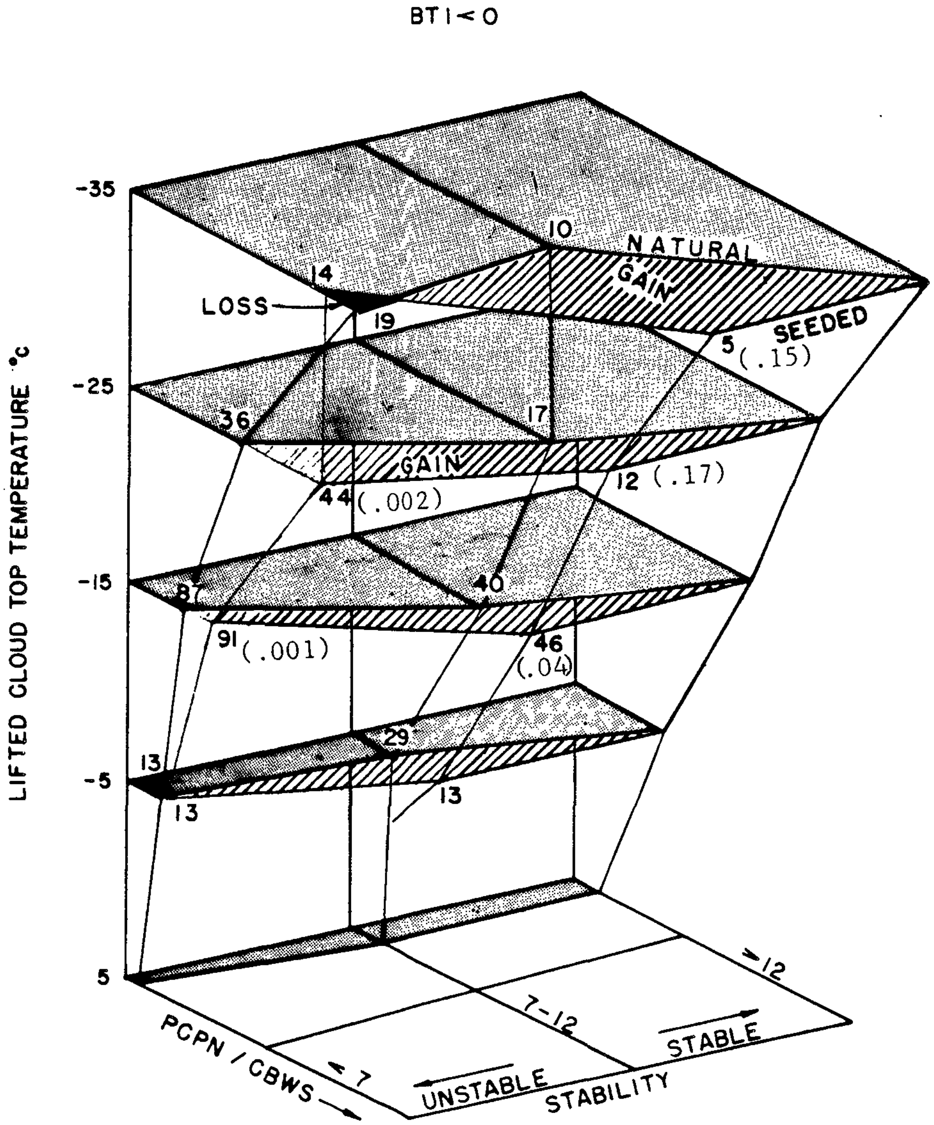

Figure 2a. Median values of the precipitation response variable for different values of the estimator variables, for negative values of barrier trajectory index. Numbers of cases for each combination are shown at corresponding vertices. Numbers in parentheses are significance levels by a Wilcoxon one-tailed test.

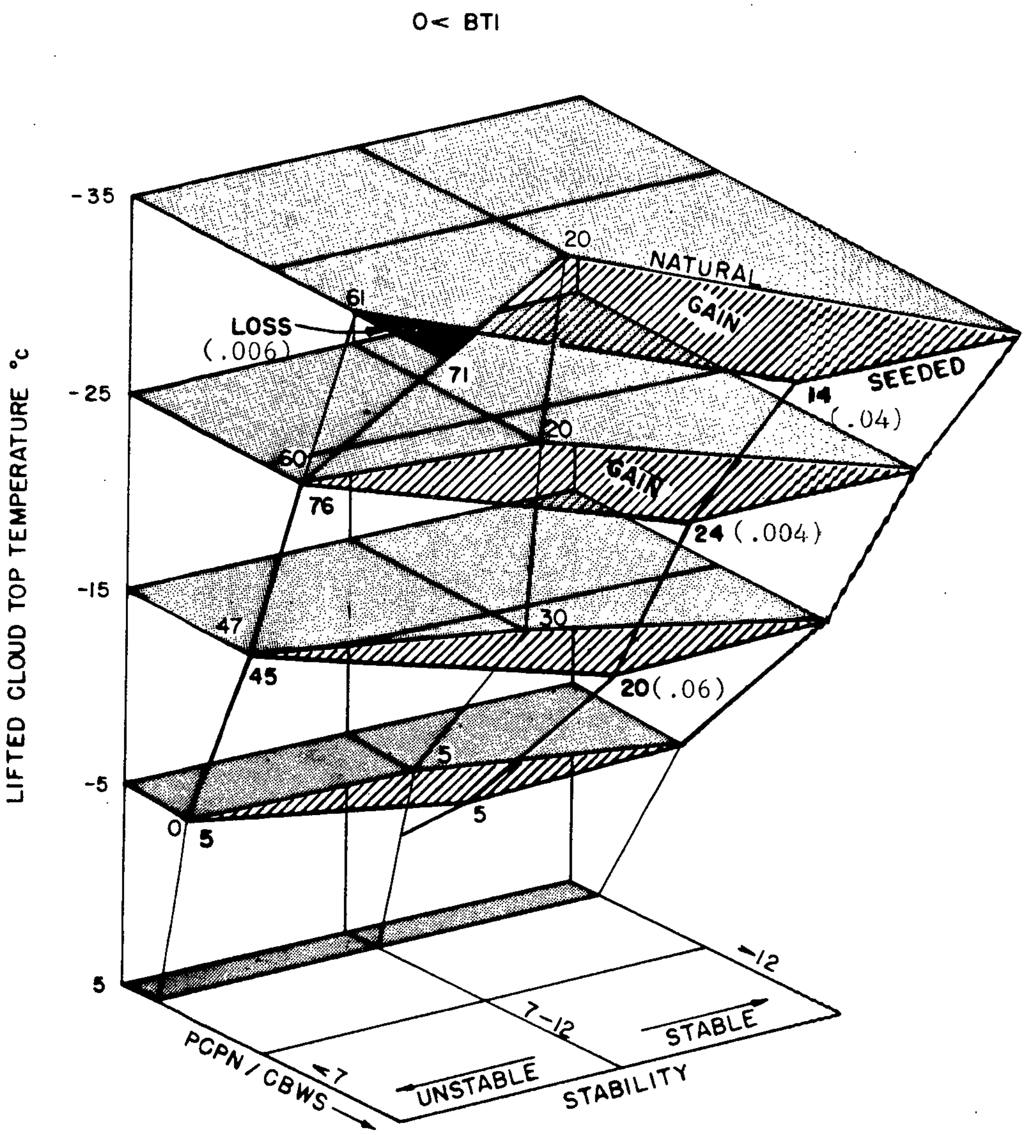

Figure 2b. Same as figure 2a, for positive values of barrier trajectory index.

Figure 3 shows, for each of the 15 categories separately, the event-by-event log of precipitation efficiencies arrayed cumulatively against a normal probability distribution. The central cross identifies a value common to all the graphs, and its vertical stroke represents a range of departures from +15 percent to -15 percent. The categories where 12 < CBWS-E were omitted because of the small number of events and lack of significance. Likewise, the highest temperature category and one of the -5°C categories were omitted for the same reason.

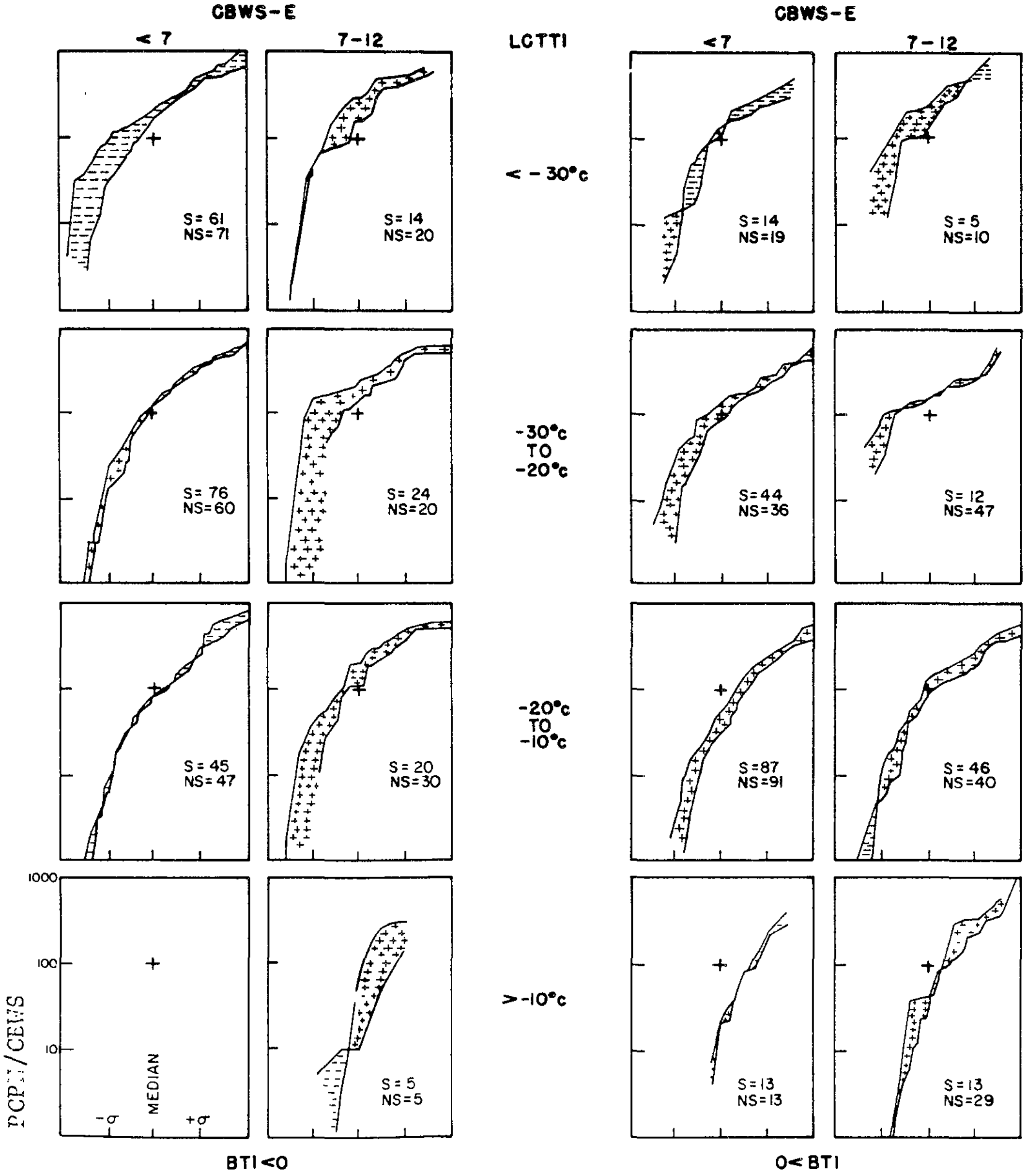

Figure 3. Cumulative frequency of occurrence of precipitation response variable for seeded, respectively nonseeded, cases for different categories of estimator indices. Positive areas indicate seeded values greater than nonseeded, negative areas the opposite. The vertical stroke of the cross near the center of each plot represents a range of response variable from +15% to -15%.

In figure 4 we have repeated selected key panels from figure 3 and shown their data separately for each of the contributing regional experiments. This figure shows the degree to which the indications of figure 3 are consistent across all the experiments.

In summary, the results presented in figures 3 and 4 show that distinctively different frequency distributions of precipitation rate occurred in different regimes defined by the estimator variables. They show also that these differences between seeded and nonseeded occasions were consistent across the variety of experimental settings, and they provide a measure of the variability remaining unexplained within each regime.

IV. DISCUSSION

We now review our original purpose - to construct a general hypothesis based on a combination of physical reasoning and empirical experience subdivided into a set of special hypotheses each of which would apply to a unique category of experimental events.

For each experimental event for which the specified set of observations is available (see table 2), the corresponding special hypothesis yields an expected value of the precipitation response variable and of its distribution about the median, for seeded and nonseeded conditions respectively. The experiment itself yields an observed value of the precipitation response variable. From these data, it is possible to accumulate evidence, event by event, as to the acceptability of the general hypothesis (as distinguished from its null) that the events actually resemble the seeded, respectively nonseeded, conditions. Developed in this form, the general hypothesis is proposed as applicable to evaluation of the Sierra Cooperative Pilot Project data and perhaps to other weather modification projects.

Table 2. - Observations that contributed to covariates

Observation	Instrument	Covariate
Wind at 70 kPa normal to barrier	Rawinsonde	BTI
Depth of cloud above ridge crest	Rawinsonde	BTI
Saturation mixing ratio at cloud base	Rawinsonde	CBWS-E, PCPN/CBWSxt
Energy releasable by convection	Rawinsonde	CBWS-E
Energy opposing convection	Rawinsonde	CBWS-E
Cloud-top temperature	Rawinsonde	LCTTI
Lifting of cloud-top over barrier	Rawinsonde	LCTTI, BTI
Precipitation rate on target	Network of recording gages	PCPN/CBWSxt

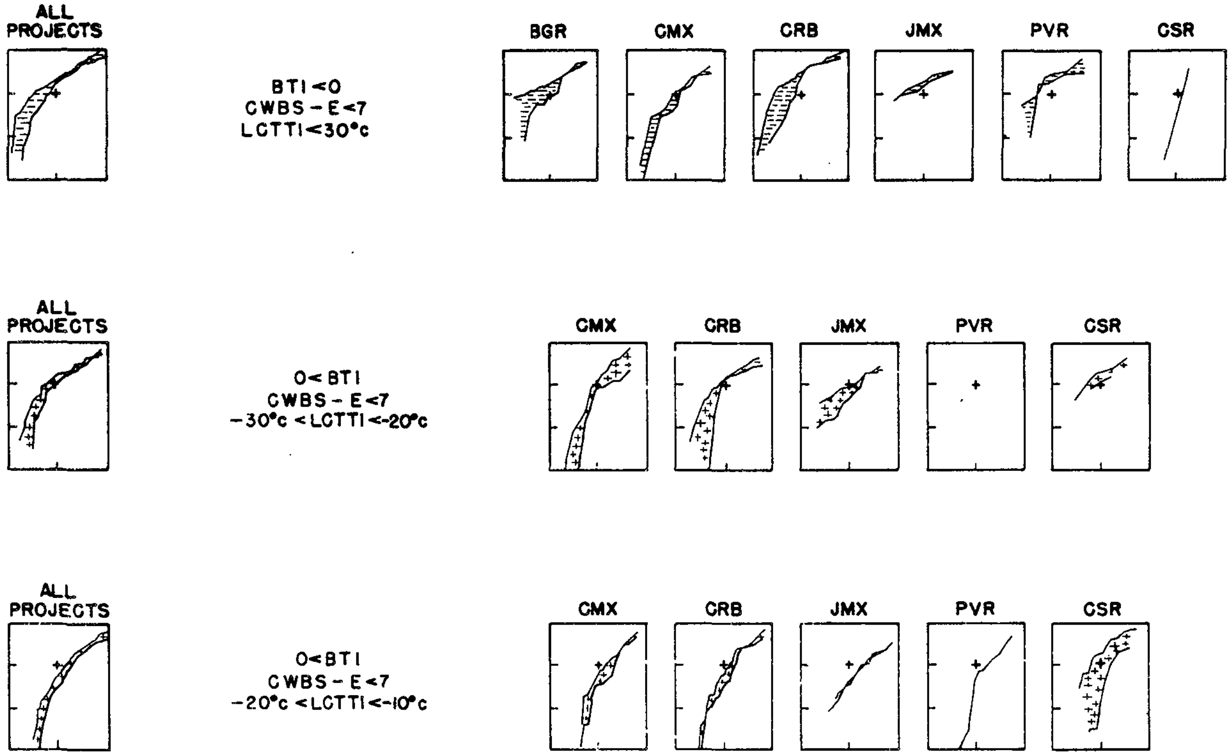

Figure 4. Combined plots from Figure 3 compared with plots from individual projects that composed them.

Now to discuss certain physical inferences.

Heretofore it has been predicted that seeding would decrease precipitation whenever the LCTTI < -30° C (e.g., Grant and Chappell,1972). The present results show this decrease only when the rise time was fast and the supply of moisture to the cloud-top region was small. In fact, in the categories of weak moisture supply at cloud top and fast rise, there was no seeding increase at any temperature when the flow across the barrier was fast.

Several explanations of this result might be proposed, involving for example the effects a changed crystal habit and number concentration on the aggregation of ice crystals into snowflakes large enough to fall. However, the data that we have considered in the present study are insufficient for resolving these matters further. They are suggested for future study involving radar observation and cloud physics aircraft sampling.

By far the most impressive increases associated with seeding occurred with intermediate amounts of moisture supply and moderate ascent rate to cloud-top level. This increase was greatest at the lowest temperature, decreasing progressively at higher tempeatures, and was somewhat greater when BTI < 0.

The precipitation efficiency was greatest with the few events when the moisture supply and time of rise to cloud top was greatest. For these events, however, no effect of seeding was indicated. Apparently the natural precipitation process in these categories is highly efficient and cannot be changed by ice-nucleus-seeding.

V. FURTHER WORK

The quantities that we have lumped into categories are continuously distributed in nature and essentially so in the data sets. Some improvement in estimate of expected values shown in figure 2 and the actual values of the independent variables are used to obtain the estimated response variable from this surface.

Inspection of figure 3 shows that the expectation of precipitation efficiency remains very unsatisfactory. In most cases, its probable error exceeds a factor of 4, and in many cases exceeds 10. Apparently some very important descriptors have been omitted or badly measured.

The variable that comes foremost to mind is the rate of air transport across the orographic barrier. As stated earlier in this paper, our attempts to improve the precipitation expectation by using the available data for windspeed normal to the barrier (at 70- and 50-kPa levels) led to disappointment. We suspect that the winds-aloft measurements in the data base, mostly derived from rawinsonde ascents made some distance upwind of the barrier, are unrepresentative of the flow actually crossing the barrier. This suspicion has considerable support from stratified-tank simulations with relief models of the terrain.

Another possibly important factor, not included in the data base, is the vertical velocity due to large-scale convergence in the cyclonic circulation.

If these surmises are correct, expectation of natural precipitation efficiencies will be greatly improved by adding measurements of windflow over the crest, and some measure of the nonorographic component of precipitation rate, in the list of estimator variables. Direct measurement of airflow across the crest may be made by a Doppler radar situated just downwind of it, such as at Donner Lake or Squaw Valley.

The notion of the overall strength of a storm as it affects the target at a given time is easy to name but hard to nail down. One can scarcely doubt that the highest points on the curves of figure 3 belong to strong storms passing directly over the target and that the lowest points belong to weak storms or those only grazing the target.

A number of possible estimators come to mind:

- Vertical velocity calculation from the National Weather Service local fine mesh grid analysis.
- Barometric pressure at the ground
- Rate of pressure fall at the ground
- Precipitation rate upwind of the barriers effect
- Precipitation rates on the barriers left and right from the experimental area
- Total number of closed isobars
- Number of closed isobars outside of the target.
- Etc.
- Any or all of the various schemes under development for objective forecasting of precipitation intensity, applied also to "nowcasting" and "hindcasting."

The possibility of improving the estimate of natural precipitation rate is perhaps the most challenging and the most significant contribution that could be made to increasing the sensitivity of any test of cloud-seeding hypothesis based on end-point productivity, namely precipitation.

MBTI (Modified Barrier Trajectory Index)

For five of the six winter orographic experiments, V-M recognized an upwind group and a downwind group of precipitation gages, and these groups are tabulated in the data base. It may be possible to expand the generality of the findings presented in this paper by modifying the calculations of BTI to apply specifically to these other groups of gages.

One of us (CJT) has prepared a set of time cross sections of 1978 winter storms in the SCPP experimental area that shows 15-min averages of precipitation in five groups of gages from the upwind valley to east of the crest, and also the depth of the blocked layer (too stable to be driven over the crest by the wind). Inspection of these cross sections shows that sometimes precipitation over the upwind valley and the foothills was at least twice as heavy as over the high country and the crest, while at other times the reverse was true. There appeared to be some tendency for the upland precipitation to exceed that in the lowlands when the blocked layer was deep and vice versa. Perhaps a deep blocked layer masks the Sierra foreslopes and decreases the effective width as well as the effective height of the barrier. If so, the cases with deep blocked layers might appropriately be treated by recalculating BTI for the narrower effective barrier.

VI. APPLICATION TO NONOROGRAPHIC CLOUD SYSTEMS

While the analysis we have presented is based on data obtained in winter orographic weather-modification experiments, the physical construct and postulates about weather modification presented in the introduction have greater generality and apply as well to convective cloud systems and extratropical cyclones. Taken together, these three categories of precipitation account for nearly all that falls on land.

Most convective systems have warmer, moister cloud bases than most orographic cloud systems and, by definition, occupy the unstable side of figures 1 and 2. However, there is a subset of convective clouds and cloud systems with cloud-base mixing ratio overlapping that of orographic cloud systems. Furthermore, it is appropriate to apply a derivative of the BTI based on rate of convective ascent to both orogrphic and nonorographic convective situations alike since even in the orographic regime the rate of ascent is governed mostly by convection when this is present. Therefore, in convective clouds and cloud systems with relatively cold bases, in the range from +10 to -5 °C, the postulated picture leads to an expectation of precipitation increase from seeding comparable in its parametric range to that occurring in relatively unstable orographic clouds.

In the subset of convective clouds with warmer bases, natural precipitation is established by the coalescence mechanism before ice nucleation can play an important role in the formation of precipitation embryos and our construct cannot be productively pursued without extending it to dynamic effects connected with the release of latent heat. This topic is beyond the range of the present contribution.

Extratropical cyclones may be regarded as causing uplift over frontal barriers directly comparable to the uplift over mountain barriers. The BTI is the only estimator variable requiring adaption; the other two can stand as they are. Our postulates, therefore, lead to the expectation that seeding will increase precipitation in cyclonic warm front situations within the parametric region indicated in figure 1, and that the experimental outcomes summarized in figure 2 might apply to experience in seeding of frontal regions of cyclones when a suitable transformation of the BTI is applied. The situation is obviously more complex, since the parameters will vary in both time and space during the lifetime of a cyclone. The principal precipitation zone of some cyclones, and some part of nearly every cyclone, would correspond to expectations of seeding effect, either increases or decreases. The intriguing possibility exists that a considerable body of past data on seeding of cyclonic disturbances could be opened to reanalysis to test these expectations.

REFERENCES

Mielke, P. W., L. O. Grant, and C. F. Chappell, 1971: An independent replication of the Climax wintertime orographic cloud seeding experiment. J. Appl. Meteor., 10, 1198-1212

Vardiman, L., and J. A. Moore, 1978: Generalized criteria for seeding winter orographic clouds, J. Appl. Meteor., 17, 1769-1777