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Research on Increased Winter Orographic Precipitation by Cloud Seeding (FY 1979) Development of Cloud Seedability Criteria

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RESEARCH ON INCREASED WINTER OROGRAPHIC PRECIPITATION BY CLOUD SEEDING (FY 1979)

DEVELOPMENT OF CLOUD SEEDABILITY CRITERIA

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ABSTRACT

This research continues the exploration of improved cloud seeding technology through the use of airborne seeding, cloud physics measurements from a research aircraft and ground based measurements for the purpose of understanding transport and diffusion of seeding material, developing seedability criteria, and documenting in-cloud responses to seeding. Development of precipitation measuring and memory devices was continued with the aim of obtaining a network of gages well suited for measurement of winter snowfall in mountainous regions.

Results of the research are highlighted by the development of criteria for seeding winter orographic storms. It was found that cloud top temperature and vertical motion apparently are the primary factors governing seedability. Indices of vertical motion are also described, so the seedability criteria can be measured readily in operational type projects.

It was found that silver iodide released from aircraft upwind of the target area did not diffuse very well by the time the plumes arrived over the target area about an hour later, so that overseeding occurred inside the plumes, and outside the plumes the clouds were underseeded.

Precipitation measurements in a target area and other locations as possible controls indicate that correlations of around 0.8 or 0.85 probably could be obtained with suitably placed gages, with the consequence that the duration of an experiment to verify a set of seeding criteria would be reduced by a factor of 3 or 4 compared to what would be required in the absence of controls.

ACKNOWLEDGMENTS

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Appreciation is also expressed for the contributions and participation of the following individuals: Duard Woffinden, electronics engineer; Brad Miller, meteorologist; Verl Bindrup, Bill Bramble and Ken Wrightsman, field technicians.

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1.0 INTRODUCTION

1.1 Summary of early experiments at UWRL

Two randomized cloud seeding experiments for increasing precipitation during winter were conducted between 1970 and 1976 in the Northern Wasatch Mountains by the Utah Water Research Laboratory (UWRL) (Hill, 1979). In the first experiment seeding material was released from an aircraft upwind of the target area. It was postulated that if the 500 mb temperature is warmer than $-22^{o}C$ the seeding would result in increased precipitation. Analysis of precipitation data in the target region showed that such a hypothesis was not supported; nor was a criterion based upon cloud top temperature.

Subsequently, a second experiment using three remotely controlled mountaintop seeding generators was carried out. In this experiment the seeding criterion was cloud top temperature. Even though cloud top temperature had not been found in the first experiment to be a usable criterion for seedability, ice nuclei measurements elsewhere (Fletcher, 1969) had indicated the cloud top temperature would be a useful indicator of seedability. It was decided that with continuous seeding over several hours, rather than two hours of airborne seeding, and with improved determination of cloud top temperature, a successful test of the cloud top temperature concept could be made. Use of predictor variables for the reduction of uncertainty of the natural variability of precipitation was also included in the experimental design. Analysis of precipitation data along with the predictor variables showed that precipitation enhancement by seeding was not identified by cloud top temperature stratification.

Finally, use of aircraft icing reports was made in order to positively identify cloud systems in which supercooled water was abundant. Reanalysis of both the airborne and mountaintop seeding experiments was made accordingly. Results indicated that seeding will increase precipitation when there is a presence of supercooled water in amounts sufficient to cause at least "light to moderate" aircraft icing. These findings were reenforced when data for the two experiments were combined.

As a result of these experiments the need to obtain in-cloud data (especially measurements of supercooled water) became evident. To follow up this viewpoint an exploratory research effort was started at UWRL. This work is summarized in Section 2.0.

1.2 Recent exploratory research at UWRL

To obtain the kind of physical understanding believed necessary to develop a sound as well as efficient seeding technology, a widely based program of inquiry was started at UWRL. Considerable progress has been made, and our recent findings and plans for the future are presented in this report.

Our recent work has been directed at finding out the detailed sequence of events resulting from the addition of seeding material upwind of a mountain barrier during periods of winter storms. This inquiry includes aspects of the problem such as the transport and diffusion of seeding material, in-cloud effects of seeding as well as the natural distribution and climatology of supercooled water, ice particles and their relationship to other more readily measured parameters such as cloud top temperature. We are interested in finding out the conditions under which supercooled water is found. Such conditions may be related to parameters not so easily measured, such as vertical motion, background ice nuclei concentrations or other factors.

In addition the measurement of precipitation on a space and time scale appropriate to the seeding delivery system and in-cloud responses is required. Furthermore, suitable covariates to precipitation are needed if the natural variability of precipitation is to be partially accounted for. We believe that the time required in an experiment conducted later to prove a promising hypothesis of seedability could be reduced by a factor of around 3 or 4 by use of suitable covariates.

Thus, the recent research at UWRL represents a marked shift in emphasis from a primarily statistical approach to one stressing physical understanding. Such understanding requires adequate data to verify or modify physical reasoning. In this way, a conceptual framework supported by physical evidence may be developed for the reliable and efficient augmentation of winter snowpack.

2.0 RESEARCH OBJECTIVES AND FINDINGS

2.1 Seeding material/delivery

An important question regarding cloud seeding is what happens to the seeding material after its release. With airborne seeding the question focuses on dispersion. Transport according to the airflow is expected to be readily predictable compared to ground released material. Diffusion of an airborne initiated plume is less well known than the basic transport, especially in cloudy conditions.

Results of our measurements to date indicate that both horizontal and vertical dispersion of silver iodide are much less than what are often assumed. Horizontal dimensions of plumes about an hour after release are typically only about 2 or 3 km, whereas the vertical dimension is typically a few hundred meters. Neither the horizontal nor vertical mixing appears adequate in an hour's time, except in unstable airflow. A more adequate dispersion time for airborne released material would be in excess of about three hours.

2.2 Cloud seeding opportunity recognition

One of the major difficulties concerning the application of cloud seeding technology is centered around the criteria used to decide whether seeding should be done or not. It is clear that for seeding winter orographic clouds, supercooled water must be present if seeding is to increase precipitation. Other parameters might be used as indices of supercooled water or of ice nuclei concentrations, but in fact, it is the supercooled water that is of prime importance. Therefore, we have sought to establish the conditions under which supercooled water is present.

So far our recent results strongly indicate that supercooled water is indeed related to cloud top temperature. However, the presence of orographic updrafts is of equal importance. In fact it is a suitable combination of the two that provide the best seeding opportunities. The presence of strong orographic updrafts, in turn, require strong airflow normal to the barrier, not very stable temperature lapse rates and cloud thickness of about 1 km or greater.

Our present findings are that seedable 'storms' are not very common, about one in five, but these relatively few will yield large increases in precipitation if the supercooled water is fully converted to precipitation.

2.3 Seeding effects in-cloud

To ascertain direct physical effects of cloud seeding, monitoring the behavior of cloud conditions within and outside of seeding plumes appears to be a sound approach. If seeding of winter orographic clouds is to be effective, supercooled liquid cloud drops must be present. Therefore, a primary concern of our research is the measurement of such liquid water concentrations and related variables. In the search for cloud seeding effects we would expect to find a reduction of supercooled water within seeding plumes. In addition to increased ice nuclei concentrations, we expect to find increased ice particle concentrations in response to the conversion of water to ice. So far our measurements show only that in a statistical sense supercooled water is depleted within the observed plumes, but insufficient evidence exists at the present time to make a direct physical connection in individual storms. Further analysis of existing data may yet show direct physical relationships. However, the problem of overseeding with plumes which are not well dispersed is a substantial one.

The consequent production of ice crystals when seeding material is placed inside a cloud containing supercooled water is less well documented at this time. However, some data do exist, but are still being analyzed; 2D Knollenberg cloud particle measurements were made during the last two test cases of FY79. More of this type of data need to be collected before the in-cloud responses to seeding are adequately understood. When such understanding is reached and suitable responses to the seeding material can be achieved, then the stage is set for finding the degree of precipitation enhancement.

2.4 Precipitation enhancement

In preparation for a definitive test of a seeding hypothesis, suitable precipitation measurements are needed. In any randomized experiment concerned with precipitation enhancement a network of gages is needed within the target area. In addition to these gages, additional ones placed far enough outside the target may be used (so that no contamination by seeding material occurs) to account for the natural variability encountered within the target. Thus, if a large amount of the natural variability is accounted for by the outside "control" gages then any seeding effects can be much more readily identified than otherwise. Therefore, our approach to finding seeding effects includes the use of control-area gages. At this stage we have obtained preliminary data for determining what correlations exist between precipitation in potential control areas and the target region. These data indicate that correlations between control and target area gages are in the neighborhood of 0.8 to 0.85 for individual storms, with the result that an experiment could be completed in about 1/3 to 1/4 of the time required in the absence of such controls.

For the present we utilize the 12" and 30" capacity Belfort gages. Later when a more accurate gage is developed and fully tested, the Belfort gages will be replaced. In the exploratory stage we believe these gages will suffice, but in any experimental program a more advanced design will be utilized.

2.5 Operational/experimental seeding designs

Our research objectives at this stage are concerned with providing input to both operational and experimental programs. For the operational programs our inputs are limited by the fact that the research is now in an exploratory stage, so that some of the findings must be regarded as tentative. Yet direct physical measurements do indeed shed some light on operational aspects. For example, our present findings strongly indicate that airborne seeding material causes overseeding within the plume, which itself is confined to a small fraction of the cloud region. Correspondingly, large areas outside the seeding plumes remain under-seeded, inasmuch as the plumes do not disperse very rapidly. Only if the airborne seeding is done far upstream (by three or more hours airflow time) can seeding material be expected to disperse adequately for relatively uniform seeding. Even then the seeding track repetition rate needs to be less than an hour or so. An alternative approach is to drop dry ice into supercooled water clouds from a jet aircraft flying above the region of aircraft icing.

Other aspects of our research strongly point to the feasibility of developing improved seedability criteria for use in operational projects.

Measurements of liquid water indicate a relationship with cloud top temperature, but other factors are also important. Furthermore, it is becoming increasingly evident that relatively infrequent episodes of liquid water occur, and that seeding efforts might well be concentrated on these cases.

Concerning experimental seeding programs our research is directed at finding out how to successfully identify seedable clouds, and then finding out how much precipitation can be augmented by seeding such clouds. To achieve these goals we intend to make certain that each step of the search is documented and that when an experimental effort is proposed all facets of the experiment can be carried out. Also, the total required time and cost of such an experiment will be known in advance.

3.0. DEVELOPMENT OF EQUIPMENT

3.1 Solid state memory system

To obtain precipitation data in digitized form with high timing accuracy we have been utilizing a solid state memory device which has been developed at UWRL by Woffinden and Hill. A brief description of this device is given by Hill (1978). Improvements in the operational reliability and field testing of the device have been attempted during this past year. These changes are as follows:

1. In the earlier design two data "banks" were utilized, each with 1000 words. Thus the capacity of the memory was 2000 words, or 20 inches of precipitation in units of one hundredth inch. The present design has only one bank, or a 10 inch capacity. The lower capacity of data storage is believed adequate if readout is made prior to the accumulation of 10 inches. In the mountains of Utah readouts at two or three week intervals are quite sufficient. As further development of the data system is made to include airborne readout, then weekly readouts can be made and no problem should exist with the size of the memory.

2. To facilitate testing and periodic checking of the memory system, several testing components have been added to the circuit board. Manual controls of these testing sequences can be operated to produce all zeros, all ones, or a sequential count in the memory bank. Then a subsequent readout of these configurations is made to confirm the integrity of the operation of each memory board. While such testing of each memory unit from time to time is desirable, it has become apparent that such testing components should be separate from the memory system units. Thus in our

future work a single testing unit will be used for all the memory boards, each of which will thereby be somewhat simplified.

3. In the previous design the readout system included a data processing package which was not part of the memory circuit board, but was a single unit located at the interface to the computer. In the current design a complete readout system is placed on each memory board. Thus a serial stream of data flows from the memory device into a computer for processing. This modification permits a readout of the memory device at nearly any computer facility.

The foregoing modifications plus the future development of airborne readout will make possible the acquisition of accurate digitized precipitation data by remote readout. Furthermore, our present design permits a rapid analysis of the data, because the data are in digital form and no keypunching, or other manual data processing procedures are required.

3.2 Precipitation gage

During the course of measuring precipitation to ascertain what are the effects of seeding on the amount of precipitation, it has become apparent that a substantial uncertainty exists in the accuracy of such measurements. Two common methods of measuring precipitation are based on 1) a weighing gage which utilizes a chart paper wrapped around a drum-clock. The weighing mechanism is a spring which causes a deflection in lever arm to which is attached a pen, and 2) a so-called tipping bucket gage which measures increments of 0.01 inch. With snowfall the 0.01 inch increments of precipitation are generated by first melting the snow as it falls into a catchment funnel. This is accomplished by the addition of a heating unit to the gage.

A substantial effort was made at UWRL to utilize the heated tipping bucket gage, primarily because of its digital type output, which was to be recorded by the solid state memory device.

Several years ago a reliable ignition system for igniting propane burners in remote areas was developed at UWRL. This development was used along with a heat control device to melt snow falling into the tipping bucket gages. Because evaporation of melting snow (being heated from below) had been found to be large, careful attention was given to the design of the heating system so that a uniform temperature just above freezing was maintained.

In early designs it was found that the ignited propane fuel caused bursts of high heat even though the duration was very short. Later, more sophisticated heating units gave improved results. However, whereas continuous heat input by a propane flame caused a reduction of catch typically 50 to 75 percent in moderate snowfall and 100 percent in light snowfall, the best heat control unit still caused a 10 to 20 percent reduction in catch as a result of evaporation. These reductions are based on amounts measured from start to finish of snowfalls by both the heated gages and weighing gages. After an exhaustive effort to design a heating system with negligible evaporation, it was decided to abandon the use of heated tipping bucket gages for measuring snowfall.

While these tests were being made at a test site near UWRL, the measurement of precipitation in the region designated as target and potential control areas was accomplished by use of Belfort weighing gages. These gages have considerable inaccuracy with respect to time and are subject to temperature effects some of which are difficult to correct for. The time errors typically run from ± .5 h up to about ± 2 h over a period of two weeks. The temperature induced errors range from about 0.05 to 0.15 inch during the course of 24 hrs. These errors occur in a somewhat regular pattern related primarily to solar heating.

In the analysis of these data attempt was made to correct for time errors by making note of the actual start and end times compared to the recorded values. Adjustment for temperature effects was also made in the analysis.

3.3 Airborne data acquisition system

The airborne data acquisition system used for the project was basically the same as previously (Hill, 1978), except for the addition of a 2D Knollenberg particle probe. The instrumented aircraft (Atmospherics, Inc.) was equipped with supercooled liquid water instruments (Johnson-Williams, Rosemount), a Mee ice particle counter, temperature, humidity, and an ice nucleus counter and a cloud particle probe (both on loan from NCAR). In addition data related to aircraft operation were also available: altitude, speed, DME, VOR, heading and rate of climb. All these data were recorded at intervals of 2.8 s or, in terms of distance at a nominal aircraft speed of 77 m s^{-1} (150 kts), about one set of readings for every 216 m traveled. The Knollenberg particle probe was operated independently of this system and data were collected over varying time intervals.

4.0 DATA ACQUISITION AND OPERATIONS

The period of data collection during the winter varied according to what was being studied. The heated tipping bucket tests were made over a period of about 4½ months. Precipitation measurements in the target and control areas were made over a period of about 3 months. Ten individual events were studied during February and the first half of March. Each event was scheduled to last about 4 hrs, but in two instances heavy aircraft icing caused early termination of the flights. For background ice nucleus measurements data were collected on four days in addition to data collected during the 10 events.

4.1 Precipitation

The layout of the precipitation-gage network for the 1978-79 winter season is shown in Fig. 1. Stations 1 and 2, Swan Lake and Willard, are the two control stations, 3 is at the UWRL test site and 4 through 11 are along the "target" line of gages. In addition to these gages a group of test gages for the study of gage performance were installed atop Beaver Mt. (site 12). Analysis of these data will be described in Section 5.

4.2 Seeding

The delivery of seeding material was designed to facilitate detection of the plumes and any direct effects on clouds in the vicinity of the plumes. Previously, the seeding aircraft was directed to fly north-south traverses, while the cloud physics aircraft flew east-west through the seeding lines downwind. However, natural variations in cloud characteristics tended to follow the same time-space pattern as

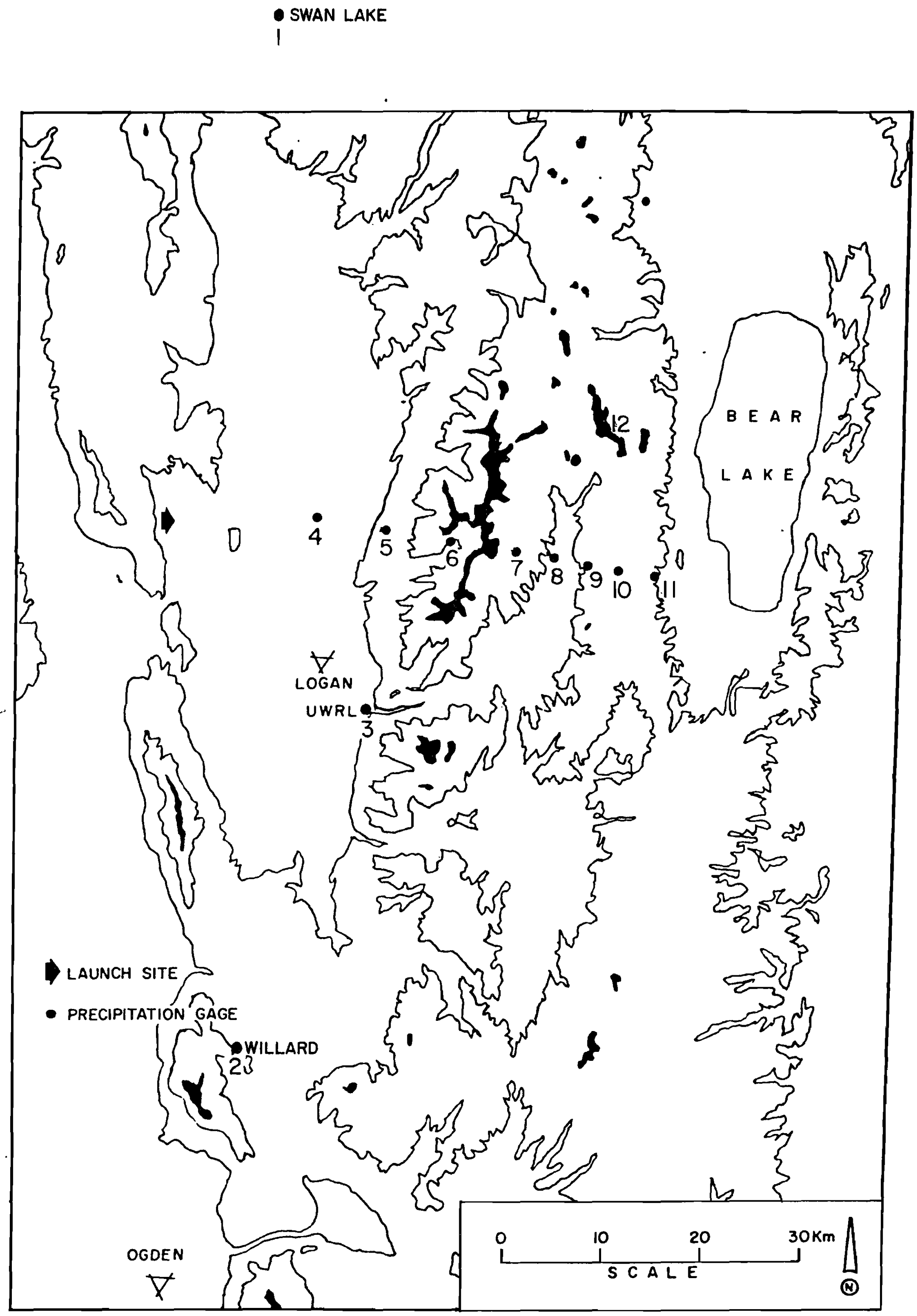

Fig. 1. Layout of the precipitation-gage network for the 1978-79 winter season.

the overall seeding plume. Therefore, it was decided this year to fly the seeding aircraft over a fixed point which was set for each event in accordance with the wind speed and direction. The seeding aircraft flew an elliptical path; the major axis was about two miles, the minor about one mile. The result of seeding from a very small area is a linear plume moving downwind, much as from a tall smokestack. In the meantime the cloud physics aircraft was flown north-south along the mountain crest to intercept the plume.

Positioning of the seeding aircraft was done in accordance with Fig. 2, in which relevant data are shown. Directions from Malad or Ogden are given and the distance along a VOR is selected to position the seeding aircraft so that the plume will arrive over the mountain crest about 40 min later. The seeding release points for each of the 10 events are also indicated on Fig. 2.

4.3 Airborne cloud physics measurements

During 10 events airborne measurements were made of supercooled liquid water, precipitation size ice particles, cloud size ice particles, ice nucleus concentrations, temperature, humidity, and other parameters concerning operation of the aircraft, including VOR, DME, rate of climb, altitude and heading. These latter parameters are needed to find the position and movement of the aircraft so that the physical parameters may be analyzed. The periods of cloud physics measurement for the 10 events are shown in Fig. 3 along with precipitation measurements at UWRL. The precipitation data are included to show the relationship of the measurement periods to storms as indicated by precipitation at UWRL.

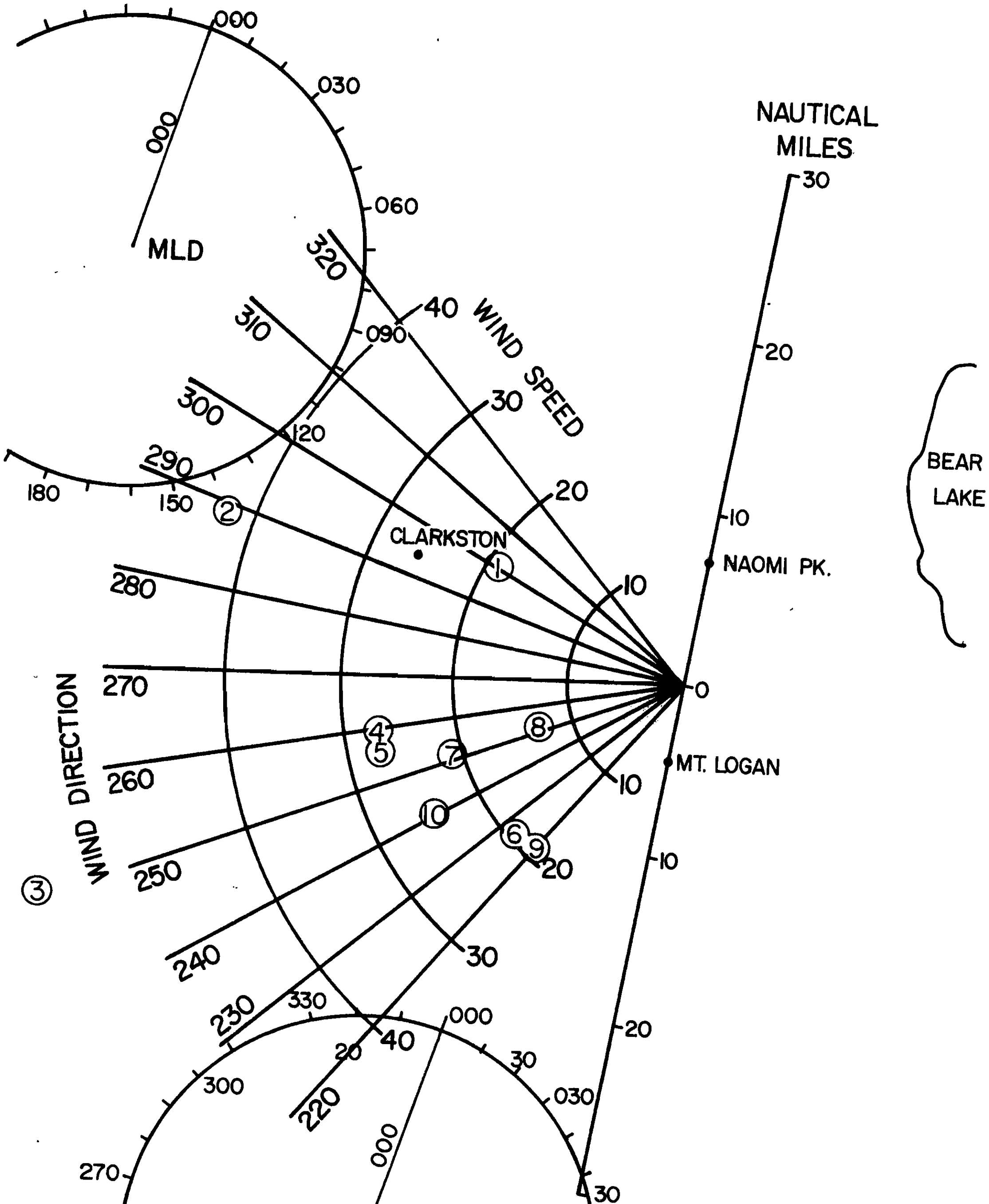

Fig. 2. Seeding release position and related information. Circled numbers indicate seeding aircraft location for each event. The release position is selected so that after 40 min the material will be crossing the cloud physics aircraft flight track.

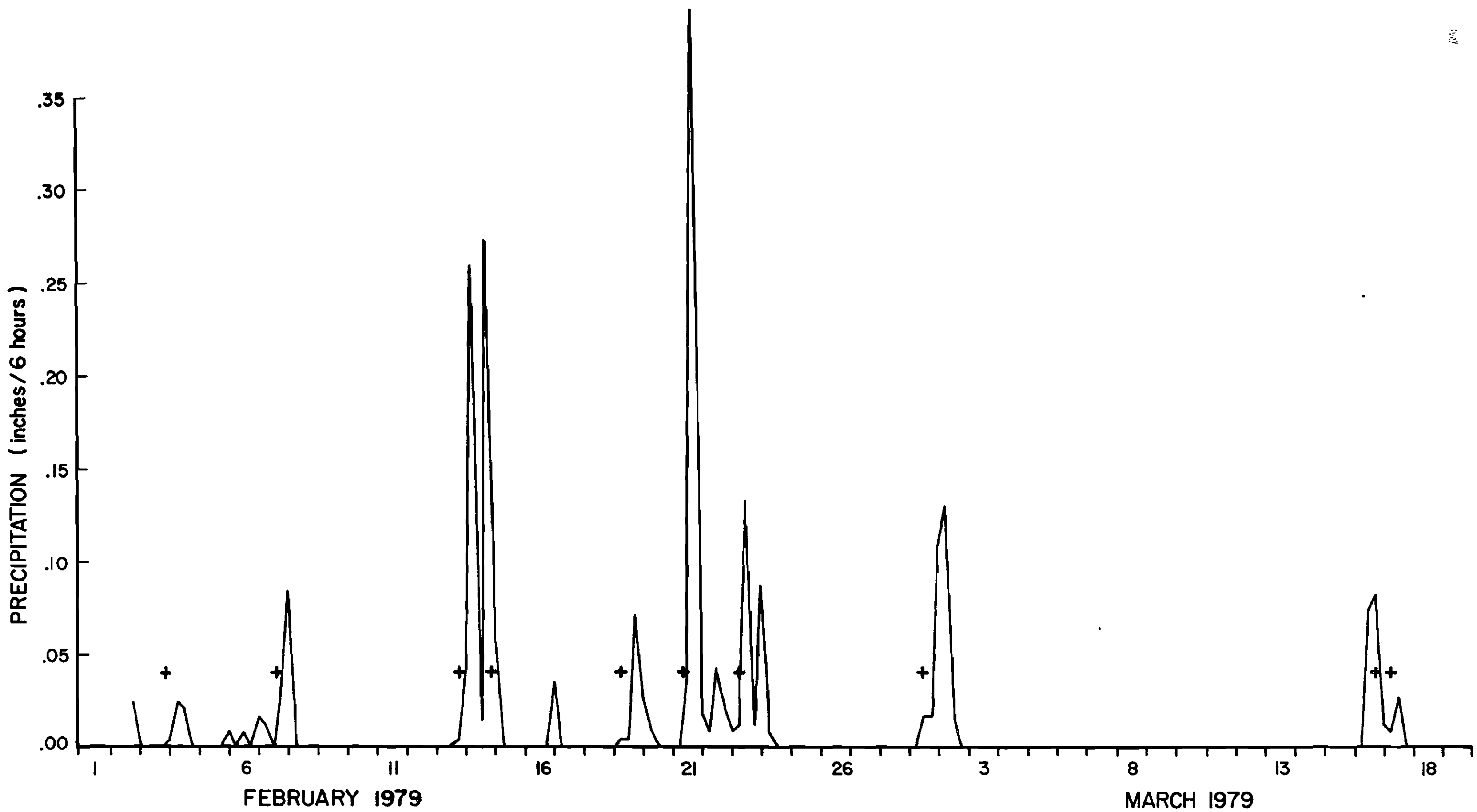

Fig. 3. Periods of cloud physics measurements and precipitation at UWRL. Crosses indicate time of events.

4.4 Upper level soundings

During each of the 10 events upper-level soundings were made to obtain data on cloud structure, airflow and stability. In addition many of the soundings included the use of the UWRL vertical motion sensing technique. Consequently, we have obtained vertical motion data from a number of storms for the third consecutive winter. These data have already shown some previously unexpected results. The new data support the previous findings of occasional strong downdrafts. Also, the occurrence of updrafts have been further documented. It is in conjunction with certain of the strong updrafts that cloud seeding may be used to greatly increase precipitation.

To summarize the operations during FY79 a list of events according to date and time along with the parameters measured is given in Table 1. In addition 11 precipitation gages were operated between February 1 and April 15, 1979.

Table 1. List of events according to date and time along with the parameters measured.

1979 Event		Airborne Measurements					Soundings	
No.	Date	Time (MST)	Supercooled Water	Ice Particles	Cloud Ice Particles*	Ice Nuclei	Vertical Motion	R/S
1	Feb. 3	2033-2333	X	✓	X	✓	0	2
2	Feb. 7	1743-1848**	✓	✓	X	X	1	2
3	Feb. 13	1952-2251	✓	✓	X	✓	2	3
4	Feb. 14	2038-2251**	✓	✓	X	✓	2	1
5	Feb. 19	0656-0957	✓	✓	X	✓	2	1
6	Feb. 21	0959-1334	✓	✓	X	✓	1	2
7	Feb. 23	1055-1325	✓	✓	X	✓	1	1
8	Mar. 1	1002-1327	✓	✓	X	✓	1	2
9	Mar. 16	1206-1415	✓	✓	✓	X	0	3
10	Mar. 16	2013-2334	✓	✓	✓	✓	3	1

*Knollenberg data.

**Flight aborted due to heavy icing.

✓ indicates measurements were made; X indicates measurements were not made.

Numbers in last two columns indicate number of soundings.

5.0 DEVELOPMENT OF CLOUD SEEDING TECHNOLOGY

5.1 Ice nuclei plumes

Two primary methods generally used for dispensing silver iodide in projects concerned with increasing snowpack are by ground generators and by airborne pyrotechnic generators. Ground based generators are advantageous either in terms of cost and areal coverage, but are not advantageous either in terms of targeting nuclei or their temporal control. The targeting difficulty of ground released material is due to a combination of thermal stability and wind variation with height. Also, the time required for material to enter a cloud may be excessively long. Furthermore, nuclei released from the ground may continue to enter a cloud long after it is desirable.

On the other hand airborne released nuclei are rather well controlled in space-time, but areal coverage is more costly. Because of the much greater knowledge of where and when seeding material will be with airborne seeding, it is worthwhile to investigate the transport and diffusion of airborne released silver iodide in the actual environment of winter orographic flow.

Evidence based upon measurements in 13 separate storms (5 from FY78, 8 from FY79) show that in most orographic storms affecting the Northern Wasatch Mountains, the downwind position of silver iodide plumes is highly predictable, but there is little dispersion of the plumes over periods of about an hour.

5.1.1 Airborne measurements of AgI. In the present study two flight patterns were utilized to release silver iodide. One pattern was a north-south track upwind of the main crest of the Wasatch. The distance was varied so that the plume would cross the barrier in about one hour from release time. The other pattern was a very small elliptical track around a fixed point. A cloud physics aircraft was flown downwind of the release position to measure the behavior of the plumes.

i) N-S released AgI. During February and March, 1978, several flights were made using two aircraft--a seeding and a cloud physics aircraft. Seeding material was released at 12,000 ft and the cloud physics aircraft was flown E-W at 12, 13, and 14 thousand feet to intercept the sawtooth pattern of material. The general finding of these measurements was that the plumes were found as expected in accordance with the positions based upon transport by wind at the seeding level. In one case the plume had risen at the rate of about 1 m s^{-1} due to vertical motion. In all plume intersections the initial indication of the presence of seeding material was found near (within about 2 mi) of the expected position. But both the maximum as well as the end of the plume were found after the expected position by 2 to 4 min, regardless of whether the flight course was eastward or westward. This latter result is attributed to the characteristics of the NCAR ice nucleus counter.

ii) "Point source" released AgI. During February and March, 1979, 10 flights were made with the two aircraft. The seeding aircraft was flown at 13,000 ft within a mile over a pre-selected position upwind of the Wasatch Mountain barrier. The cloud physics aircraft was flown generally N-S along the barrier crest at altitudes of 12, 13, and 14 thousand feet. Thus, the cloud physics aircraft made successive passes through an approximately point source plume.

5.1.2 Evaluation of measurements. A sample of the measurements made is shown in Fig. 4. The number of "NCAR counts" (counts per 2.8 seconds) is shown against time. The concentration of nuclei per liter is approximately the total number of counts per minute. If the response time of the ice nucleus counter were nearly instantaneous, then the 5 minute spread of the plume could be interpreted as a plume of 20 km width. Such apparent widths (D) are shown in Fig. 5 against a maximum amplitude, A, (NCAR counts) multiplied by the distance downwind from the source.

The apparent widths increase nearly linearly as the magnitude of the counts adjusted for distance from the source. However, it is rather unlikely that we would find the strongest plumes in excess of 20 km wide and the weakest ones less than 1 km even with plume interceptions off center.

These uncertainties concerning measured and actual diffusions can be clarified by examining the measured counts with respect to the actual position of the aircraft. A typical in-cloud situation is depicted in Fig. 6. The track of the cloud physics aircraft (C) is shown along with times and altitudes. The track of the seeding aircraft (13,000 ft) is shown with the label S. The long bar indicates the expected position of the AgI plume at the two times it is crossed by the cloud physics aircraft, i.e., 0811 and 0822 MST. The magnitude of the ice nucleus concentration at half minute intervals is shown along the track as a histogram. The maximum values shown here are just about as high as any encountered throughout all the flights. It is therefore probable that the flight track was near the maximum concentration in the vertical direction. A

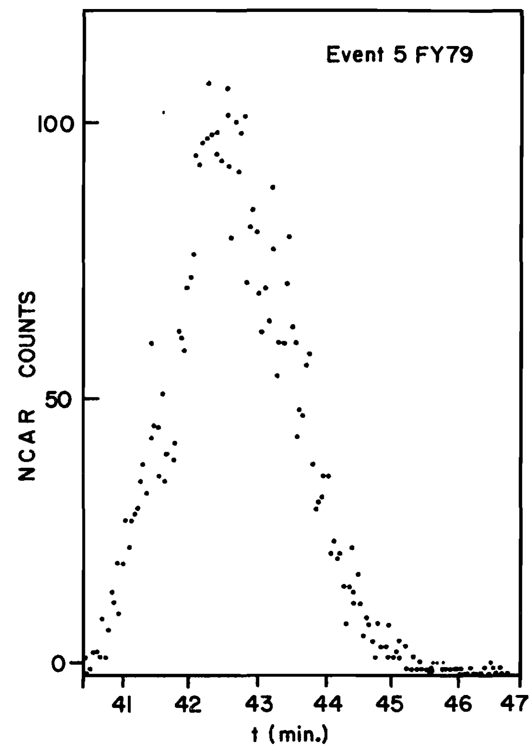

Fig. 4. Ice nucleus counts per 2.8 s versus time, from 0840:15 to 0847 MST 19 Feb. 1979.

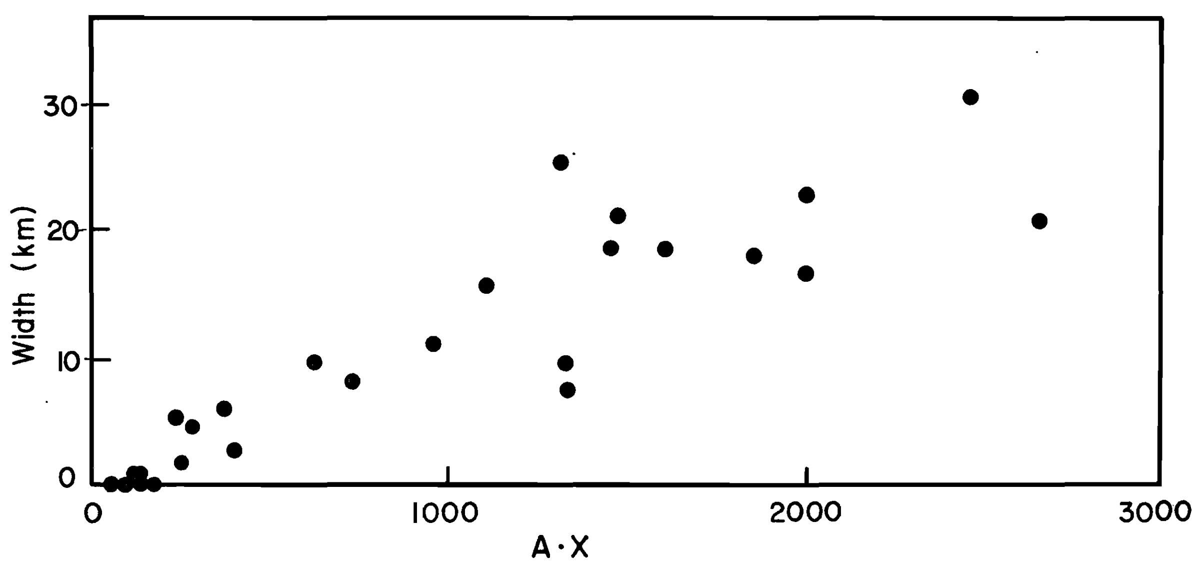

Fig. 5. Apparent plume width (D) versus A·x, where A equals average of ten highest counts in each plume.

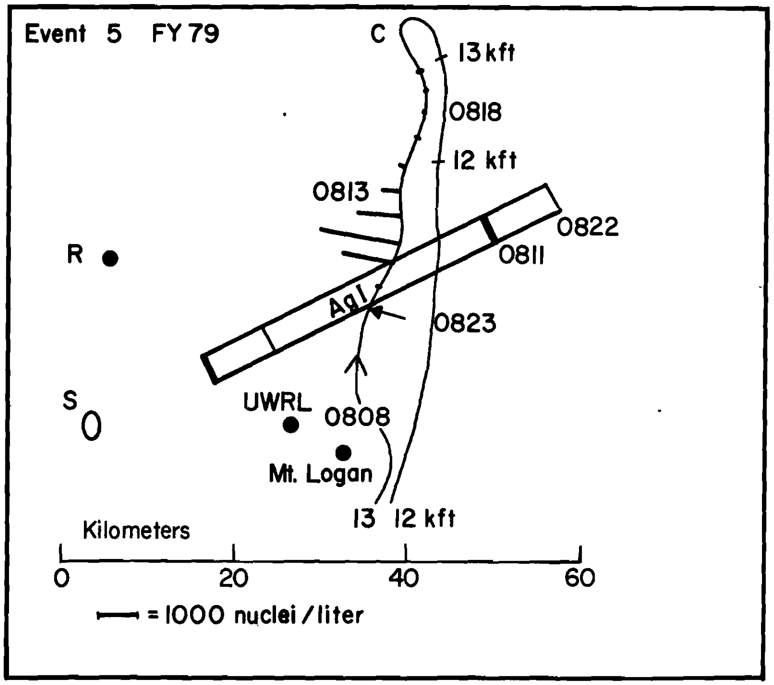

Fig. 6. Cloud physics (C) and seeding (S) aircraft tracks with plume positions at interception times and histogram of ice nucleus counts per liter, on 19 Feb. 1979. Arrow pointing toward flight track indicates start of plume interception. (R) indicates the position of the rawinsonde.

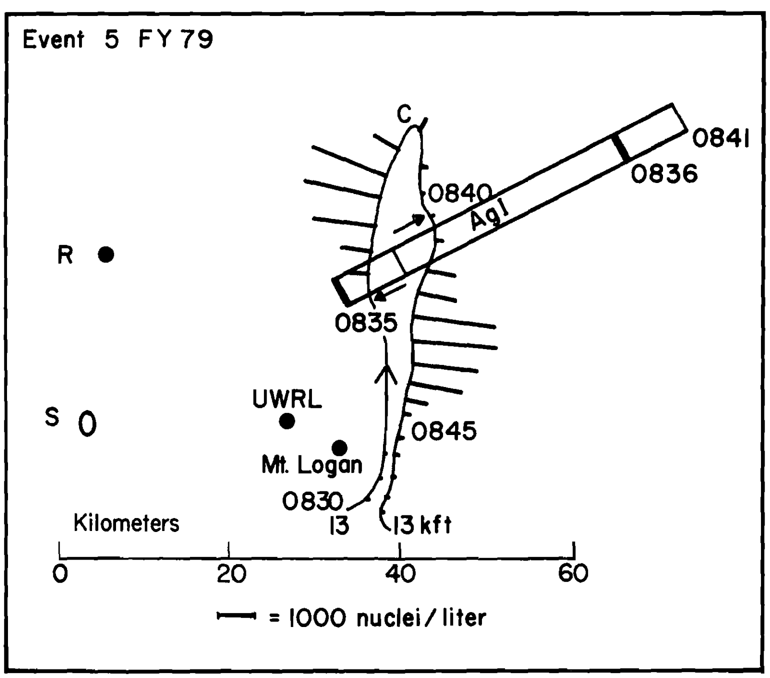

Fig. 7. Same as Fig. 6 at later time.

small arrow pointing sideways toward the track shows the initial indication of the plume's presence. On the return southward leg the flight altitude was 12,000 ft; no ice nuclei were detected. Thus, the vertical dispersion of the plume in nearly one hour was less than 1,000 ft.

The next round trip of the cloud physics aircraft is shown in Fig. 7. Here the plume has advanced downwind, but interceptions of the plume in both directions are evident. The time lag of the maximum indicated values is clearly evident. The reason for the lag between actual and measured maximum ice nucleus concentration is due primarily to the time required for collisions between water droplets and the small ice nucleus particles. On the other hand the initial onset of the plume as indicated by the arrows shows a much more restricted plume than the apparent width previously discussed. (See also Fig. 4.) There is a small time lag of the initial onset, which amounts to about 30 s (Heimbach et al., 1975). Thus, the horizontal spreading of the plume on each side is no more than about 2 or 3 km over and above the initial value. The spreading could indeed be less if meandering of the seeding aircraft beyond its scheduled track had occurred.

Finally, it is stated that the detailed measurements described herein are typical in the following respects: 1) the vertical gradients of nuclei counts are typically strong, with near maximum counts at one level and zero counts at a level 1,000 ft up or down; 2) the initial rise of nuclei counts is found within about 2 km of the expected undiluted plume position; 3) the time lag of the ice nuclei counts is such that a maximum of counts is recorded about 8 or 10 km down track from the expected position.

We conclude that both the vertical and horizontal diffusion of silver iodide in most orographic storms in the Northern Wasatch Mountains are much lower than that desired for effective seeding. The vertical diffusion coefficient K_z is estimated to be of the order of $3\ m^2\ s^{-1}$, and the horizontal diffusion coefficient K_x is typically less than around $50\ m^2\ s^{-1}$. The horizontal spreading speed of a plume's edge is typically less than $1\ m\ s^{-1}$. Consequently, airborne seeding results in a small fraction of the clouds to be greatly overseeded, while the remainder of the clouds is not seeded.

It has been shown that dispersion of silver iodide from airborne generators is generally much less than that desirable for effective seeding operations in winter orographic clouds. Alternative measures are: use of ground generators (with similar and other problems), seeding much further upwind, or use of dry ice--to eliminate the vertical diffusion problem. In view of the various problems with silver iodide (diffusion, temperature-activation spectrum), it appears that use of dry ice pellets might be advantageous. "Activation" depends only upon the presence of supercooled water; the downwind cold region effects of AgI are largely absent with dry ice; dry ice can be dropped from high altitudes above icing conditions; and there is little question of environmental effects of the required amounts of CO_2.

5.2 Vertical motion

The presence of supercooled water is of paramount importance if the addition of artificial ice nuclei is to cause an increase in precipitation over what would occur naturally. We can reason that the occurrence of high concentrations of liquid water in the form of cloud droplets is a result of vertical updrafts within a saturated (cloud) environment.

Consequently, the characteristics of vertical updrafts are important. The conditions leading to updrafts, the magnitude and location of updrafts are of specific interest. At the same time, we are interested in knowing which clouds will be converted to precipitation efficiently by natural means and which ones will not. It is this latter factor wherein cloud top temperature presumably has its utility.

5.2.1 Measurements and analysis of vertical motion. Recently, vertical motion measurements were made during passage of several cold fronts in the Northern Wasatch Mountains (Hill, 1978). Based upon these measurements it was found that downdrafts sometimes occurred in winter orographic storms as a result of precipitation drag and possibly evaporation. While the associated updrafts (giving rise to precipitation in the first place) were not emphasized in that study, there is nevertheless a definite pattern of updrafts associated with frontal passages in the Northern Wasatch Mountains. Such a pattern is exemplified by an individual case as shown in Fig. 8. In this particular case the downdraft was larger than usual. What is of interest here is the presence of an updraft near mountaintop levels (3 km). The height of the updraft tends to increase as time passes. The thickness of the layer of rising motion is about 2 km in this particular case.

Data collected in two subsequent winters strongly support the initial findings. An example of the vertical profile of vertical motion is shown in Fig. 9. Here the updraft extends over a vertical layer of 1.5 km. The thickness of the layer with vertical motion above 1 m s^{-1} is less than 1 km.

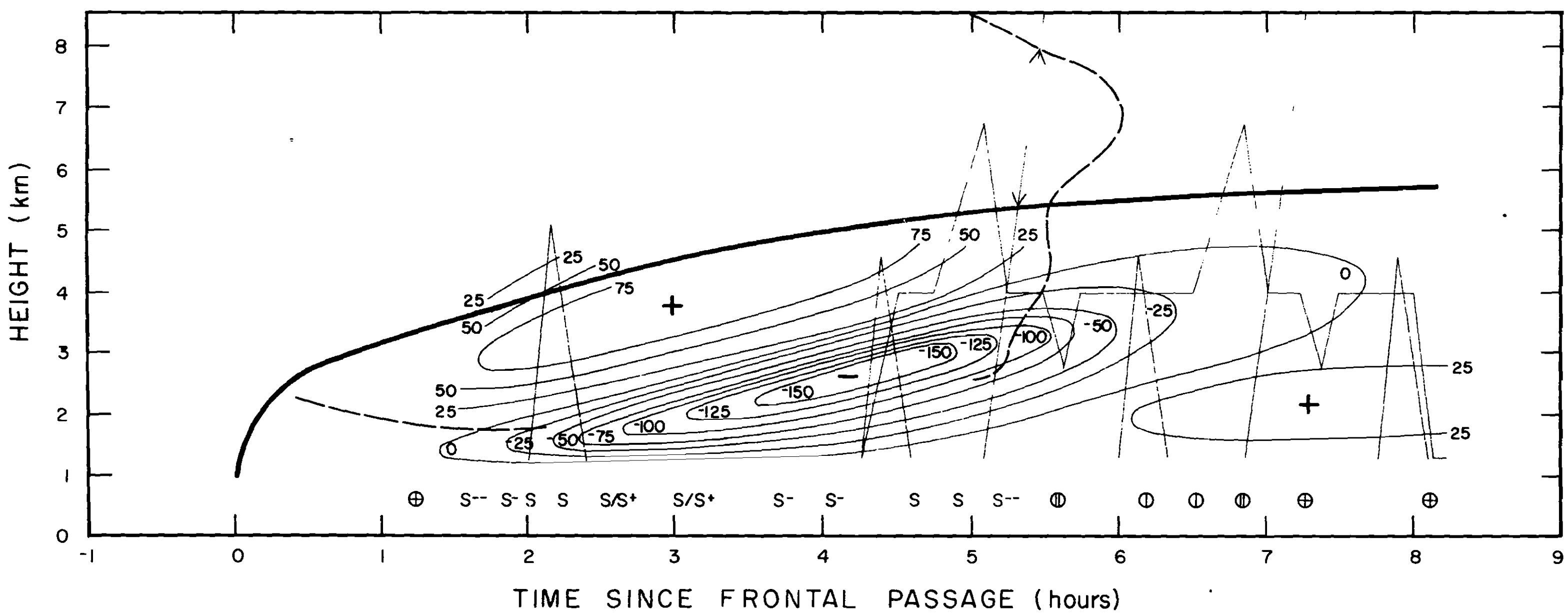

Fig. 8. Height-time sequence of upper level data for event 77-5. Contours of vertical motion at 25 cm s^{-1} intervals. Cloud bases and tops as observed from aircraft and rawinsonde data are shown by dashed curves. Carets on rawinsonde flight track indicate cloud base and top. Cloud cover and precipitation at Richmond are shown along bottom line. Freezing level is below the ground. Height is in kilometers above sea level.

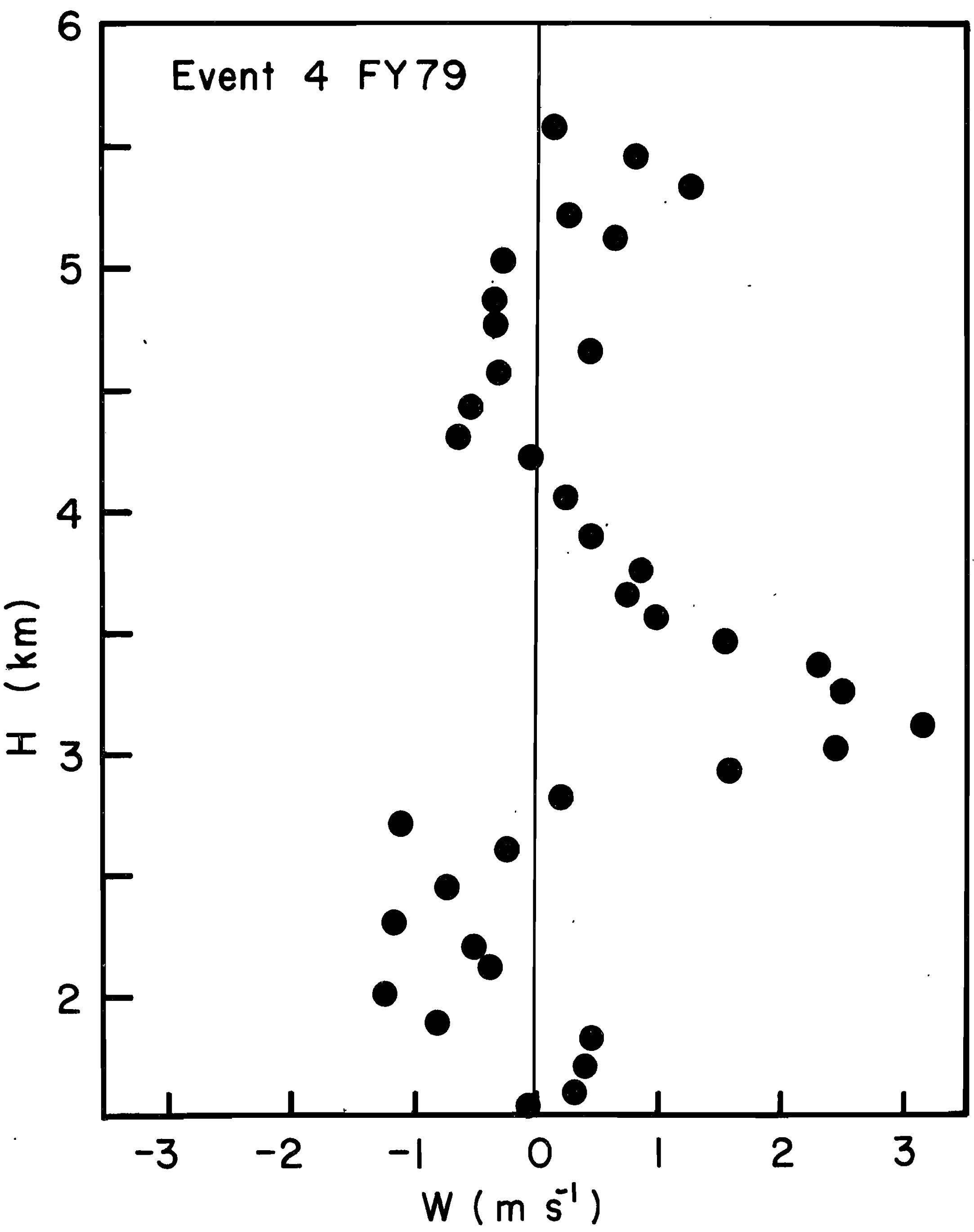

Fig. 9. Vertical profile of vertical motion, 2230 MST 14 Feb. 1979.

Data from other cases over the three winters of measurement show that the thickness of the layer of rising motion is usually between 0.5 and 1.5 km, as shown in Fig. 10; the same is true for the thickness of downdrafts. Also we note that downdrafts occur somewhat less frequently than the updrafts (5 downdrafts, 17 updrafts). There is virtually no dependence of the thicknesses on the distance to the front.

The vertical locations of updrafts and downdrafts are shown in Fig. 11. The heavy dots or open circles indicate the location of the maximum updraft or downdraft, respectively. The typical location of the updraft maximum is between 3 and 4 km elevation, and between 2 and 3 km elevation for the downdraft, if present. There is a small tendency for the updraft to occur at a higher elevation at a greater distance behind the front.

The magnitude of updraft and downdraft maxima is shown in Fig. 12 according to distance from the front. The updrafts tend to reach a maximum just about the time of the frontal passage, or slightly after. Note the large number of measurements indicating near zero maxima. These measurements are usually associated with rather weak fronts. Downdrafts occur much less frequently than updrafts. The downdrafts reach maximum strength generally 200 to 300 km after frontal passage.

In all of the measurements where the maximum vertical motion was 1 m s^{-1} or greater (7 cases) the vertical temperature stability was low. That is, a parcel lifted moist adiabatically from 750 mb to 550 mb showed a temperature with respect to the ambient of no more than $2^{o}C$ colder. Such weak stability does not guarantee an updraft; it is apparently a necessary condition.

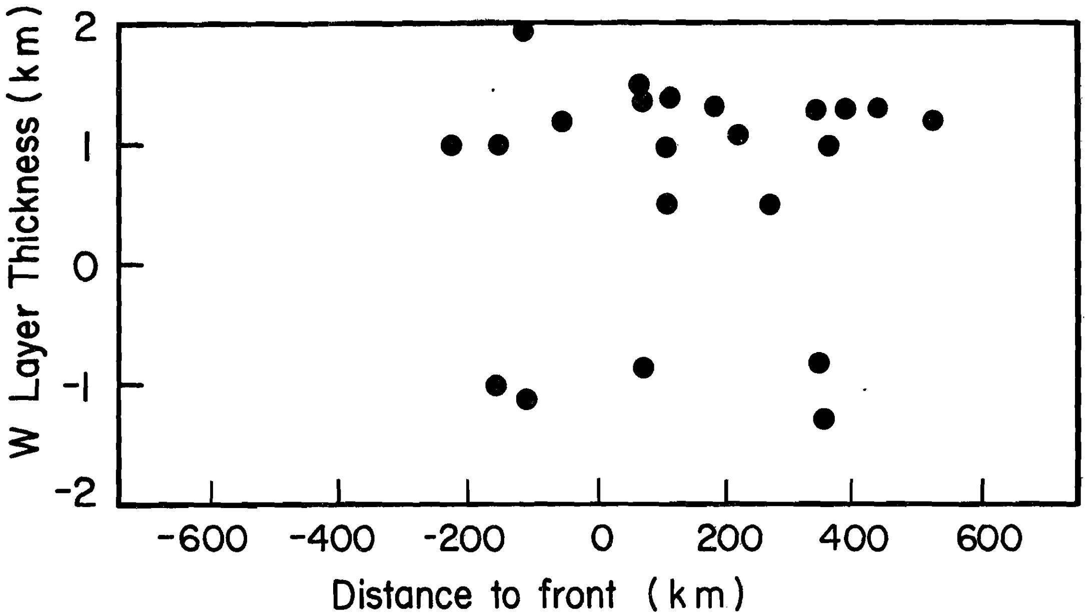

Fig. 10. Thickness of vertical motion layers versus distance to front. Negative distance indicates pre-frontal; negative thickness indicates downdraft.

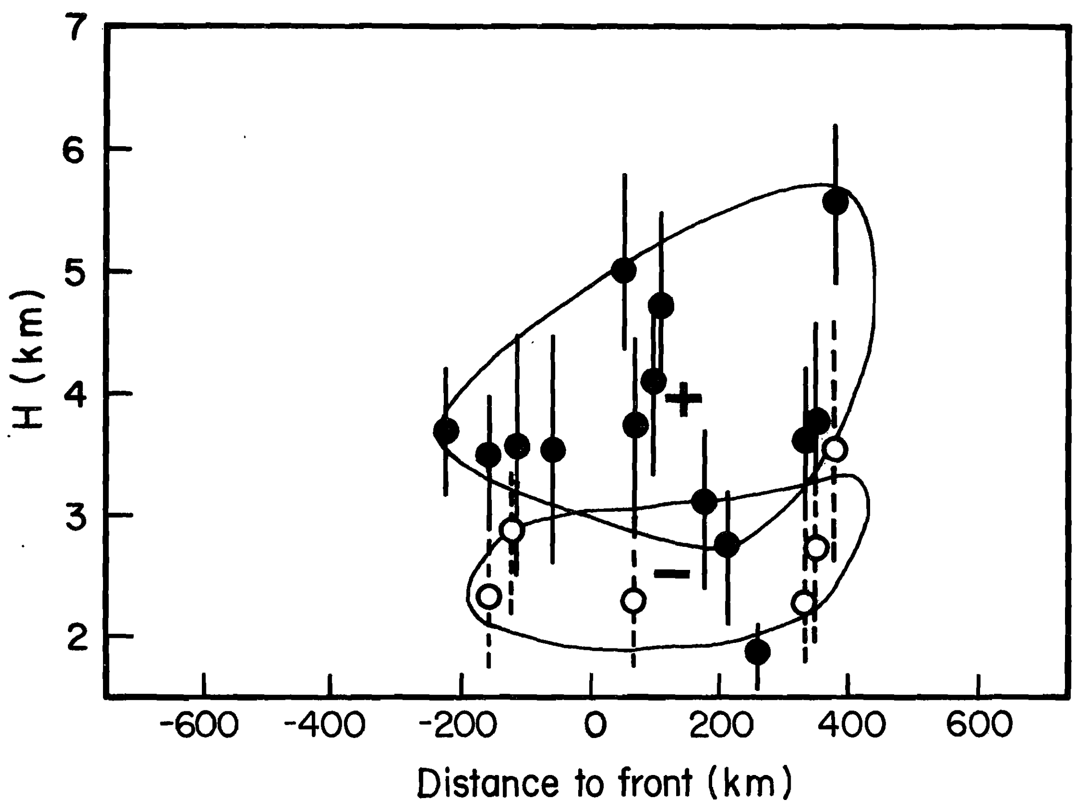

Fig. 11. Vertical location of updraft and downdrafts versus distance to front.

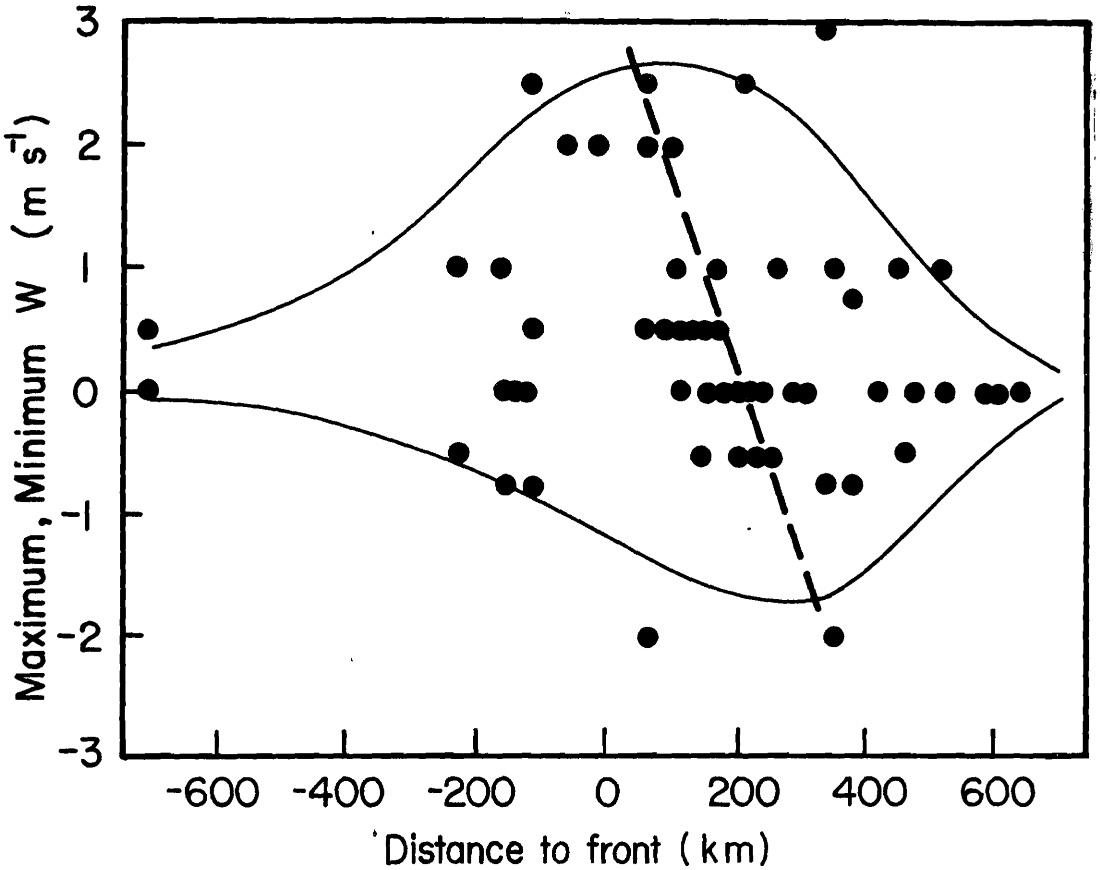

Fig. 12. Magnitude of maximum updrafts and downdrafts for each sounding versus distance to front.

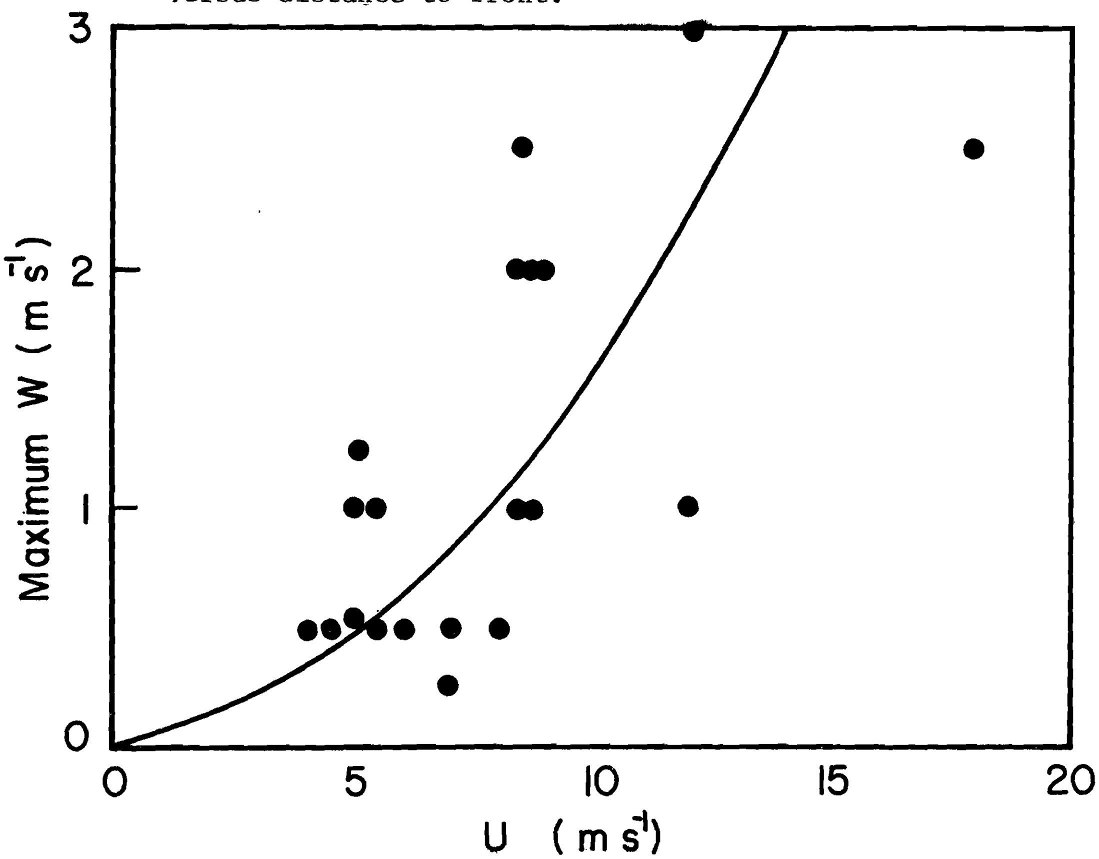

Fig. 13. Maximum updraft versus wind speed normal to the barrier at 3 km elevation.

As shown in Fig. 13 the maximum updraft is plotted against the wind speed normal to the barrier at 3 km elevation. As the wind speed increases so does the maximum updraft. Whether the three conditions of saturation, temperature stability and wind flow are sufficient as well as necessary for the formation of an updraft is not yet known. However, these data do suggest that seedability at least requires a not too stable lapse rate and adequate wind.

5.2.2 Relation of vertical motion to supercooled water. If as stated previously we can relate the distribution of supercooled liquid cloud water to in-cloud vertical motion, then it can be said that supercooled water will be found in relatively thin layers compared to typical cloud masses over mountains. The very high values of liquid water will be confined to layers of about 0.5 km thickness. Such layers, if not converted to precipitation, would be found in the vicinity of fronts, as much as 200 km in advance, to 400 km behind the front.

Yet these are the locations wherein precipitation is greatest and the cloud tops typically the highest and coldest. So the occurrence of high concentrations of supercooled water is likely to be infrequent. In a recent study Hill (1979) notes that substantial aircraft icing was reported in only one out of every six storm events. This present study supports this proportion. Furthermore, when supercooled water does occur, reports of aircraft icing are widespread, and not usually confined to a small band within many of the storms.

5.2.3 Implications for seeding technology. We may conclude that a preferred type of cloud suitable for seeding is associated with post frontal clouds with not very stable lapse rates, but strong mountaintop winds normal to the barrier. This conclusion does not state that stable orographic clouds do not offer the possibility of increased precipitation by seeding, but rather that episodes of high concentrations of supercooled water are instead associated with post frontal conditions described above. Seeding of stable orographic clouds may have some modest benefit, but seeding of certain of the post frontal clouds may have dramatic benefits.

5.3 Supercooled water and in-cloud ice particle measurements

5.3.1 Supercooled water measurements. Supercooled water measurements were made during each flight by two instruments, the Johnson-Williams hot wire device and the Rosemount icing rate probe. The output of the J-W device is converted directly into gm/m^3 of supercooled water, whereas the output of the Rosemount probe is in depth of icing (due to supercooled water). A detailed calibration/comparison between the J-W and Rosemount data has not yet been completed, but is underway. In the meantime, the Rosemount data are being used in the analyses. This preference is based primarily on the fact that there is a drift in the base (zero) value of the J-W output. With the aid of the Rosemount data, such drift can be accounted for. On the other hand the Rosemount icing probe operates reliably and appears to yield consistent readings.

5.3.2 In-cloud ice particle measurements.

i) Mee ice particle counter. Until recently the only project measurements of in-cloud ice particles have been made with the Mee ice particle counter (IPC). It is evident that these IPC measurements refer to precipitation size particles rather than newly formed ice crystals as might be found shortly after the injection of seeding material.

Comparison of IPC and supercooled water shows that the two quantities have a strong tendency to be mutually exclusive, as previously indicated on the basis of other data. This partitioning of water/ice forms can be seen by comparing the location of supercooled water and ice particles along the various flight tracks of FY78 and 79. When the two forms are found together it is due to the (rapid) conversion of supercooled water into ice. So upwind of such a region the predominant form will be supercooled water, and downwind will be ice particles.

ii) 2D Knollenberg probe. During the winter of 1979 a 2D Knollenberg probe (on loan from NCAR) was added to the cloud physics aircraft. Atmospherics, Inc. personnel along with our staff and that from Particle Measuring Service attempted to install the probe and make it ready for collecting data on newly formed, or small ice particles. Several problems were encountered, including the discovery of some undocumented modifications to the timing system for data sampling. Toward the end of the project, the most serious problems were resolved and some data were collected.

The specific purpose of the data collection effort was to obtain ice particle data before, during and after passing through airborne released silver iodide plumes. Sample data are shown in Fig. 14. The width of each column of data is approximately 1 mm. Thus, ice particles fully shown in the 2D depictions are generally small or very small snow particles. Analysis of these data will be given in Section 5.5.

5.4 Analysis of seedability

5.4.1 Supercooled water versus ice particles. In this section the relationship between supercooled water and ice particles is described. Generally, ice particles appear as a result of conversion of supercooled

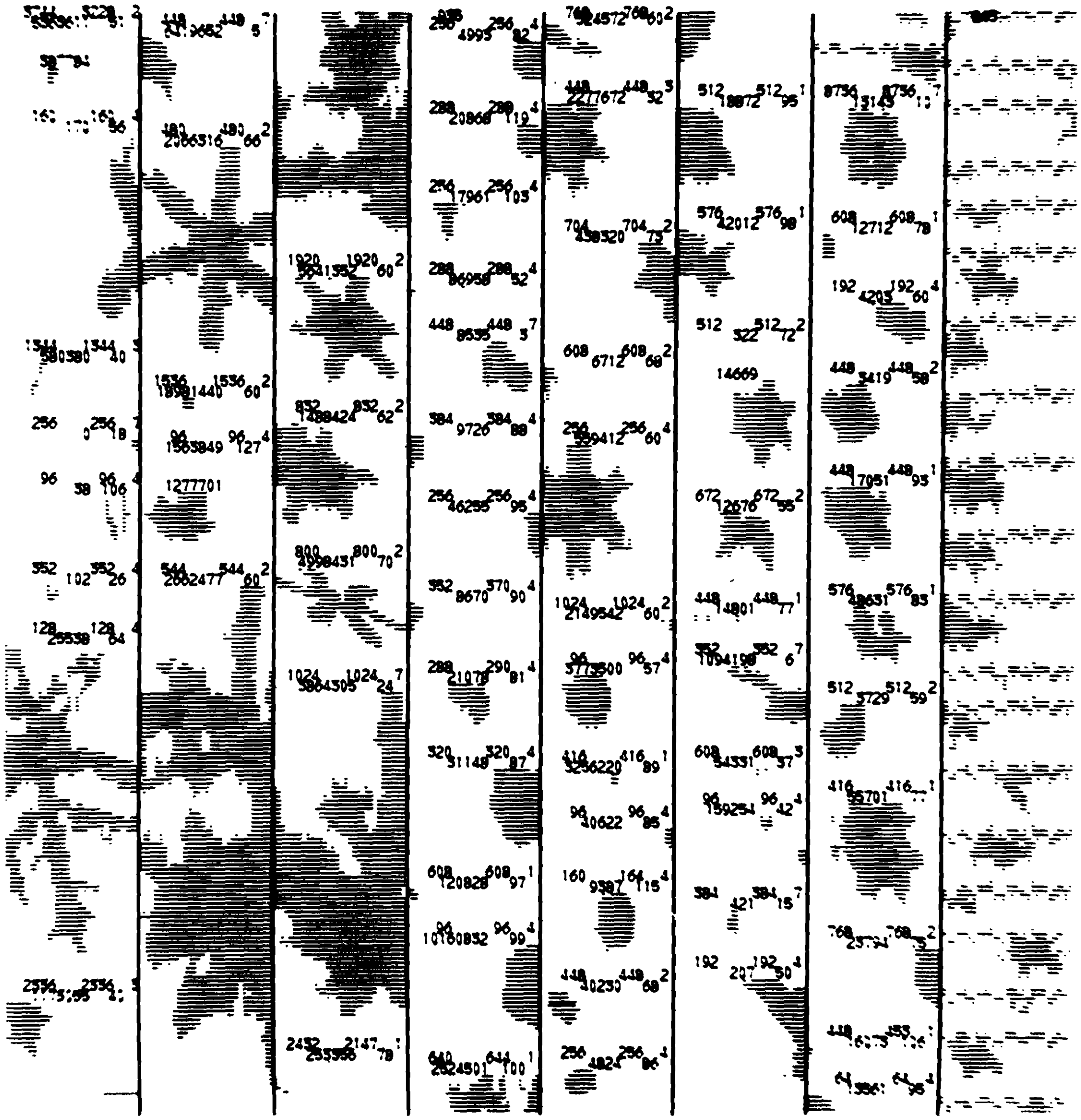

Fig. 14. Sample 2D Knollenberg cloud particle images for event 79-10 (2224:45-2226:26 MST, 16 Mar. 1979). For increasing time read down from right to left.

water to ice, or by direct conversion of water vapor to ice. Thus, it is to be expected that when ice crystals are present, supercooled water is sometimes found nearby. Because the conversion of supercooled water is often very rapid there is a tendency for the two water phases, liquid and solid, to be mutually exclusive.

A graph of supercooled water as measured by icing rate and ice particles is shown in Fig. 15 for 20 min measurement periods. During these periods the cloud physics aircraft travels approximately 80 km, so both supercooled water and ice crystals are often found. However, there is strong tendency to have a separation between the two water phases, that is, either the presence of one phase but not the other.

When the time period is reduced to two minutes there is a still greater tendency for the two water phases to exist exclusively. The two minute icing rates and ice particle counts are shown in Fig. 16. Here nearly all the data are found along either axis. In both figures almost all the data points are below the curve shown.

The conclusion of this finding is that supercooled water is an unstable state and that if precipitation occurs, most of the supercooled water disappears. Thus, we tend to have an either/or situation; either seeding will initiate precipitation or seeding is not needed if precipitation is occurring.

5.4.2 Relationship of LWC, IPC with vertical motion and cloud top temperature. Because vertical motion is apparently a useful indicator of the amount of water vapor converted to supercooled water and ice, and cloud top temperature is believed to be an indicator of the availability of ice forming nuclei, we shall explore the relationships of these variables with supercooled water and ice particles, i.e., precipitation.

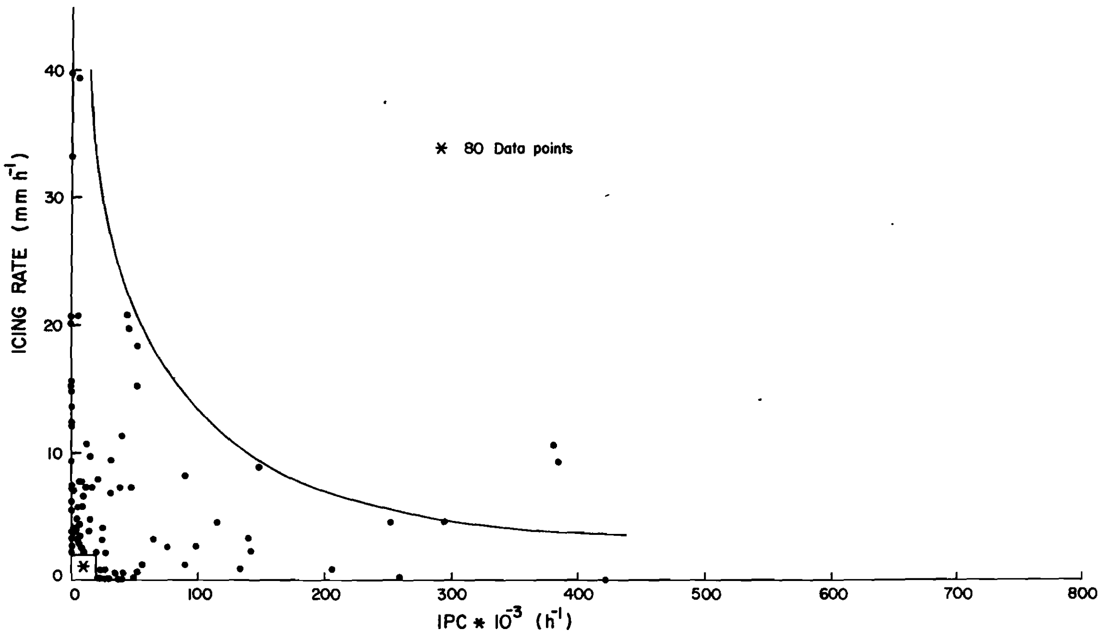

Fig. 15. LWC versus IPC for events in FY78 and FY79 for 20 min periods (consecutive).

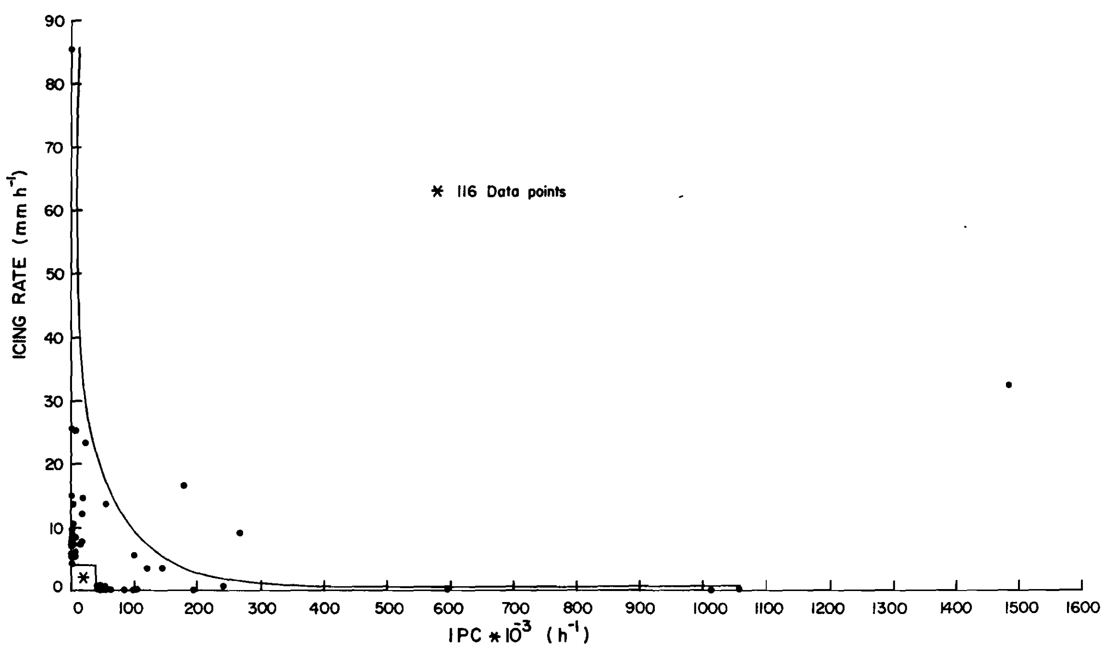

Fig. 16. LWC versus IPC for events in FY78 and FY79 for 2 min periods (sampled every 10 min).

Values of the various parameters relevant to this particular analysis are listed in Table 2 for both FY78 and 79. These are the cloud top temperature, average hourly precipitation rate for the event, the maximum vertical velocity averaged for the available soundings in each event, and an icing rate parameter. In addition a "seedability ratio," which is the icing rate parameter divided by the precipitation, is listed.

The icing rate parameter is found as follows: the accumulation of ice in millimeters for each of five 20 km segments of flight path having the highest accumulation rates is added together (22 min flight time) and multiplied by 2.7 to give an hourly icing rate. This result tends to emphasize areas or periods with the higher concentrations of supercooled water. The reason for this particular parameter is that in FY78 the flight path was across the barrier, whereas in FY79 the flight path was along the barrier crest. The parameter given above tends to reduce differences due solely to the flight path. It should be noted that an analysis using average values of icing rates over each event does not substantially change the results to be described below.

In Fig. 17 icing rates (mm/hr) measured at 13,000 ft are plotted as a function of the maximum vertical velocity and cloud top temperature. Although it would be highly desirable to have more data such as these, there is a fairly good indication that when the vertical motion is weak or the cloud tops are cold there is little supercooled water. When the cloud top temperature is relatively warm, vertical motion causes an increase in supercooled water; when cloud top temperatures become colder there is a depletion of supercooled water by precipitation. Therefore, the shape of the contours in Fig. 17 is as expected if the

Table 2. Values of parameters relevant to the analysis of seedability and seedability criteria: cloud top temperature, CTT; vertical motion, w; icing rate, I; precipitation rate, p; seedability ratio, SR; and position of cloud physics aircraft with respect to clouds.

Event		CTT °C	w[1]	Icing[2]	Precipitation[3]	Seedability Ratio	Aircraft[4]/ Cloud
78	1	-13	-	22	-	-	IN
	2		-	-	-	-	IN
	3	-45	-	10	-	-	IN
	4	-22	-	19	-	-	IN
	5	-35	220	2	13	0.2	IN
	6	- 6	75	1	0	∞	OT/HLA
	7	-14	60	56	0	∞	IN
	8	-12	40	19	0	∞	OT/HLA
	9	-12	60	6	0	∞	OT
	10	-18	110	26	5½	4.7	IN
79	1	-40	-	-	0	-	IN
	2	-14	250	82+	5	16.4	IN
	3	-40	25	2	½	4.0	I/O
	4	-25	290	43	13	3.3	IN
	5	-23	35	0	0	∞	IN
	6	-25	50	0	2	0.0	IN
	7	-13	50	1	3½	0.3	OT
	8	-21	50+	23	0	∞	IN
	9	-17	-	26	1	26.0	IN
	10	-21	140	25	½	50.0	IN

[1]Average maximum updraft cm s^{-1}.

[2]Measured over 100 km with highest icing rate (mm hr^{-1}).

[3]Hundredths inch per hour, averaged over period of cloud physics aircraft on track flight.

[4]Abbreviations:
- IN In cloud
- OT On top of cloud
- I/O In and out of cloud
- HLA Higher cloud layer above

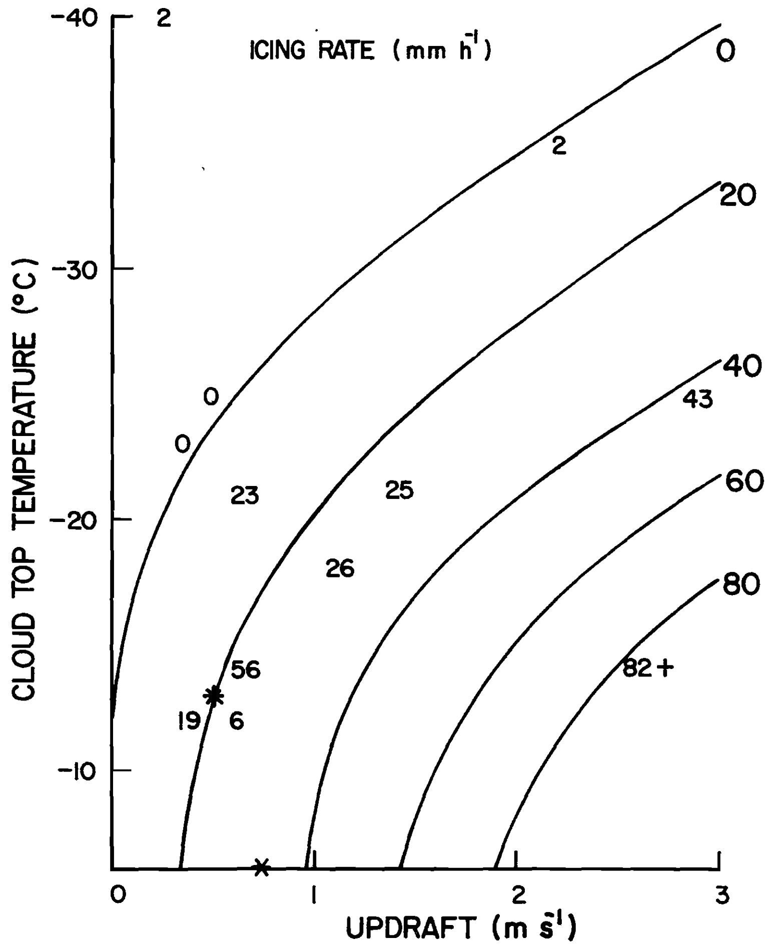

Fig. 17. Icing rates versus cloud top temperature and average maximum vertical motion

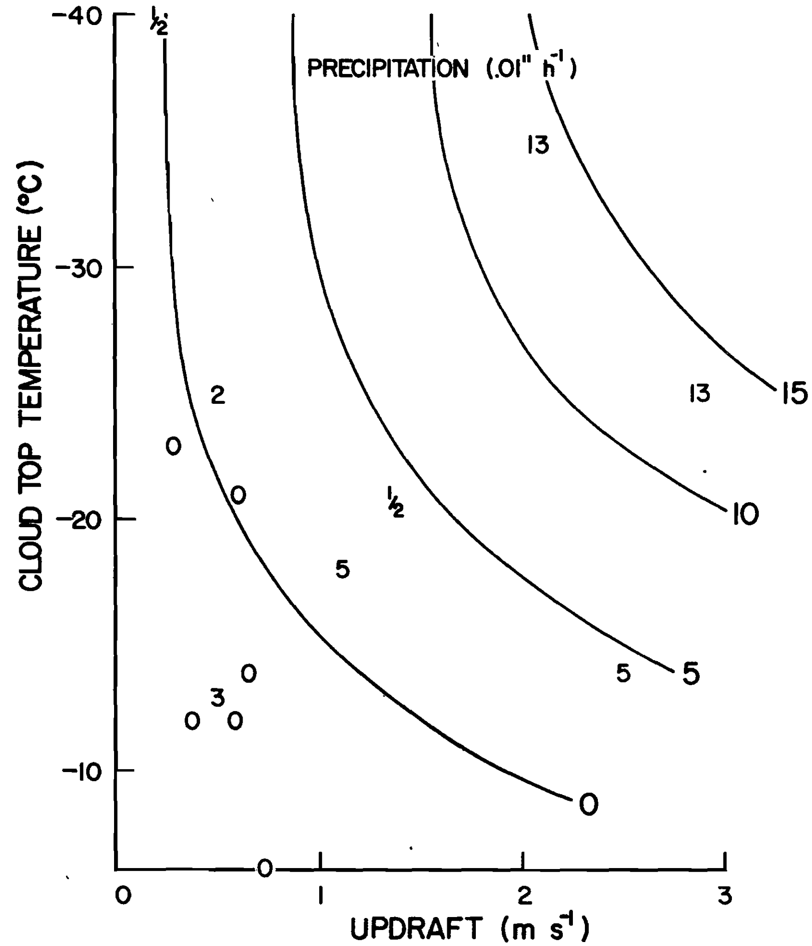

Fig. 18. Hourly precipitation rates at Smithfield Canyon versus cloud top temperature and average maximum vertical motion

foregoing is true. The main point in question is whether precipitation does indeed occur mainly at high values of vertical velocity and cold cloud top temperatures.

In Fig. 18 values of hourly precipitation rates at Smithfield Canyon, averaged over the same time period as the in-cloud measurements, are plotted as a function of w and CTT. Again it would be desirable to have more data to confirm or refute the apparent finding, which is that precipitation does indeed occur mostly when there is strong vertical motion and cold cloud top temperatures.

5.4.3 Seedability ratio and seeding criteria. As a measure of seedability we divide the icing rate by the precipitation rate. So, if there is little icing and substantial precipitation the seedability ratio (SR) will approach zero. On the other hand if the icing rate is high and there is little or no precipitation then the ratio will approach infinity. The seedability ratio may be expressed in general as $SR = LWC/p$, where p is a precipitation rate. Depending upon the availability of data some measure of the supercooled water concentration and precipitation is required to evaluate SR. In our case we use icing rates which are directly related to supercooled water concentrations and hourly precipitation rates at Smithfield Canyon.

The seedability ratios for available FY78 and FY79 data are shown in Fig. 19. From these data it appears that with cloud top temperatures of $-22^{o}C$ and warmer there is a seeding potential. However, it is pointed out that even with an infinite SR the actual amount of increase from seeding may be small.

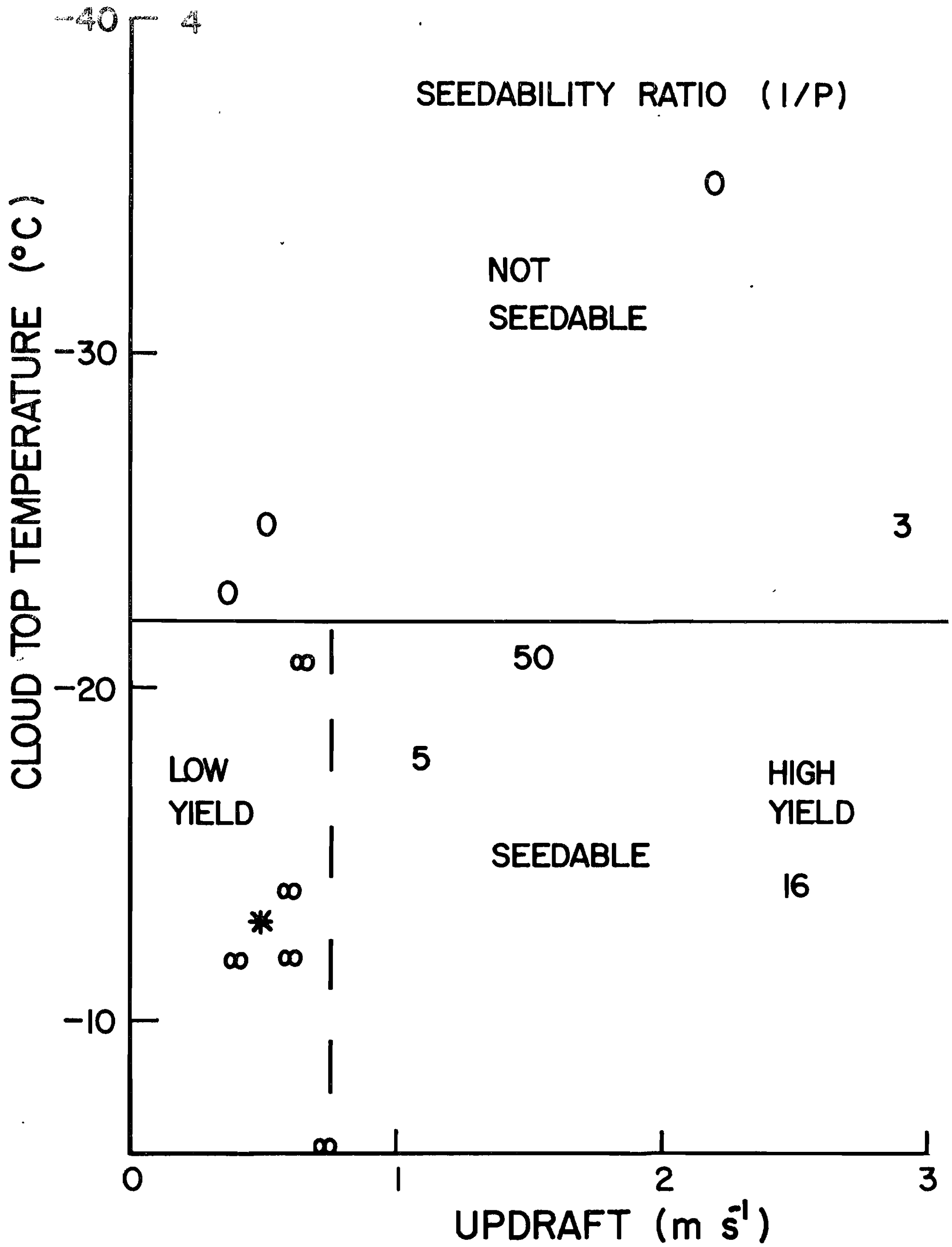

Fig. 19. Seedability ratios versus cloud top temperature and average maximum vertical motion

The largest increases from seeding would be expected when both the actual amounts of supercooled water and the SR are high. Thus, only three of the 14 events (21 percent) represented in Fig. 19 are considered worthwhile for seeding. Even two of these may be considered marginally seedable. The 21 percent figure may be compared with 17 percent found in an earlier study (Hill, 1979).

To identify which cloud systems contain updrafts of a magnitude sufficient to produce substantial LWC we examine the meteorological conditions associated with such updrafts. It was pointed out (Hill, 1978) that episodes of strong vertical motion in orographic storms can occur only if the vertical temperature profile is not very stable. Or in other words, as might commonly be expected, updrafts occur within clouds when the lapse rate approaches or exceeds the moist adiabatic rate.

In addition we have noted a relationship between updrafts and mountaintop wind speed normal to the barrier (Fig. 13). It is also noted that the cloud depths associated with substantial vertical motion are generally at least 1 km.

Therefore, we conclude that the following criteria may be used as indices of seedability if direct measurements of LWC and w are not used. All of the criteria must be present for the clouds to be considered seedable:

1. Cloud top temperature $-22^{\circ}C$ or warmer,
2. In-cloud temperature lapse rate with respect to the moist adiabatic rate less than 1 or $2^{\circ}C$ per km,
3. Mountaintop wind speed normal to the barrier in excess of $8\ m\ s^{-1}$ (15 kts),
4. Little or no precipitation occurring in target area, and

5. Cloud depth at least 1 km.

Conditions 2, 3 and 5 actually are approximate conditions representing updrafts exceeding 75 cm s^{-1}, and it is recognized that the cloud top temperature limit may vary from storm to storm.

When the above criteria are satisfied it is highly probable that large amounts of supercooled water are present and that appropriate seeding could be expected to cause substantial increases in precipitation. By "appropriate seeding" it is meant that seeding material must be effective at its ambient temperature and that the seeding material must be diffused or well mixed continuously over the period of seeding.

5.5 Analysis of seeding effects

5.5.1 Supercooled water and ice particles. To ascertain direct physical effects of cloud seeding, monitoring the behavior of cloud conditions within and outside of seeding plumes appears to be a sound approach. If seeding of winter orographic clouds is to be effective, supercooled liquid cloud drops must be present. Therefore, a primary concern of our research is the measurement of such liquid water concentrations and related variables. In the search for cloud seeding effects we would expect to find a reduction of supercooled water within seeding plumes. In addition to increased ice nuclei concentrations, we expect to find increased ice particle concentrations in response to the conversion of water to ice.

Our present data suggest 1) that high LWC is found in about one out of every five or six storm periods, and 2) that supercooled water is generally absent within seeding plumes.

In addition the search for direct effects wherein the seeding material causes a reduction in supercooled water will continue. The difficulty of this search arises out of the great local variability of LWC even though high LWC may be present over a wide region.

The consequent production of ice crystals when seeding material is placed inside a cloud containing supercooled water is less well documented at this time. However, some data do exist; 2D Knollenberg cloud particle measurements were made during the last two test cases of FY79. More of this type of data need to be collected before the in-cloud responses to seeding are adequately understood. When such understanding is reached and suitable responses to the seeding material can be achieved (through optimum delivery and seeding agent), then the stage is set for finding the degree of precipitation enhancement.

It is expected that if seeding material is causing a reduction of supercooled water by converting the water to ice crystals, then at the time of this conversion we should observe an increase in the concentration of ice particles, which would at first be a relatively small size compared to precipitation particles. With present seeding delivery and weak diffusion, we should expect to find large numbers of ice particles within the plumes.

5.5.2 Analysis of Knollenberg ice particle data. In three instances Knollenberg cloud particle data were collected during passage through an ice nucleus plume. In all three cases the plume was relatively weak; in one pass during event 9 the aircraft was on the top edge of the plume, and in two passes during event 10 the aircraft passed through the tail end of a previously strong plume at its primary altitude.

During passage through the ice nucleus plume in event 9 the Rosemount icing detector indicated a slow increase in icing, thus documenting the fact that the aircraft was in cloud. The ambient air temperature was $-10^{o}C$. Ice particle images before passage through the plume are shown in Figs. 20 and 21 and during passage, in Fig. 22. Unfortunately, a power failure prevented collection of any cloud particle data until about 10 min later. However, the change in particle size and number density upon entering the plume is substantial. Prior to intercepting the plume the cloud particles were consistently much larger and less abundant than during passage. Also, when data were collected later the ice particles were similar to that collected prior to intercepting the plume.

During the two plume interceptions in event 10 the Rosemount icing detector indicated a reduction in icing, due to sublimation. Ice particles were relatively infrequent compared to those of event 9 and the size was variable. A sample of the data from event 10 is shown in Fig. 23. It is noted that the particle size was somewhat smaller than those prior to and during passage of the plume, but their number density was much lower than in event 9.

In summary, the measurements made with the Knollenberg ice particle probe indicate that inside a cloud an ice nucleus plume such as produced by airborne seeding will result in the production of a great many very small ice particles. Although this statement must be regarded as tentative, because of the very limited ice particle data, the concept is as expected from a physical point of view, inasmuch as measurements of airborne generated ice nuclei frequently show a large overseeding in narrow plumes. What is actually desired is the appearance of some ice crystals but not large concentrations. In the latter case we have accomplished overseeding. Prior to the commencement of any proof-of-concept experiment, our seeding

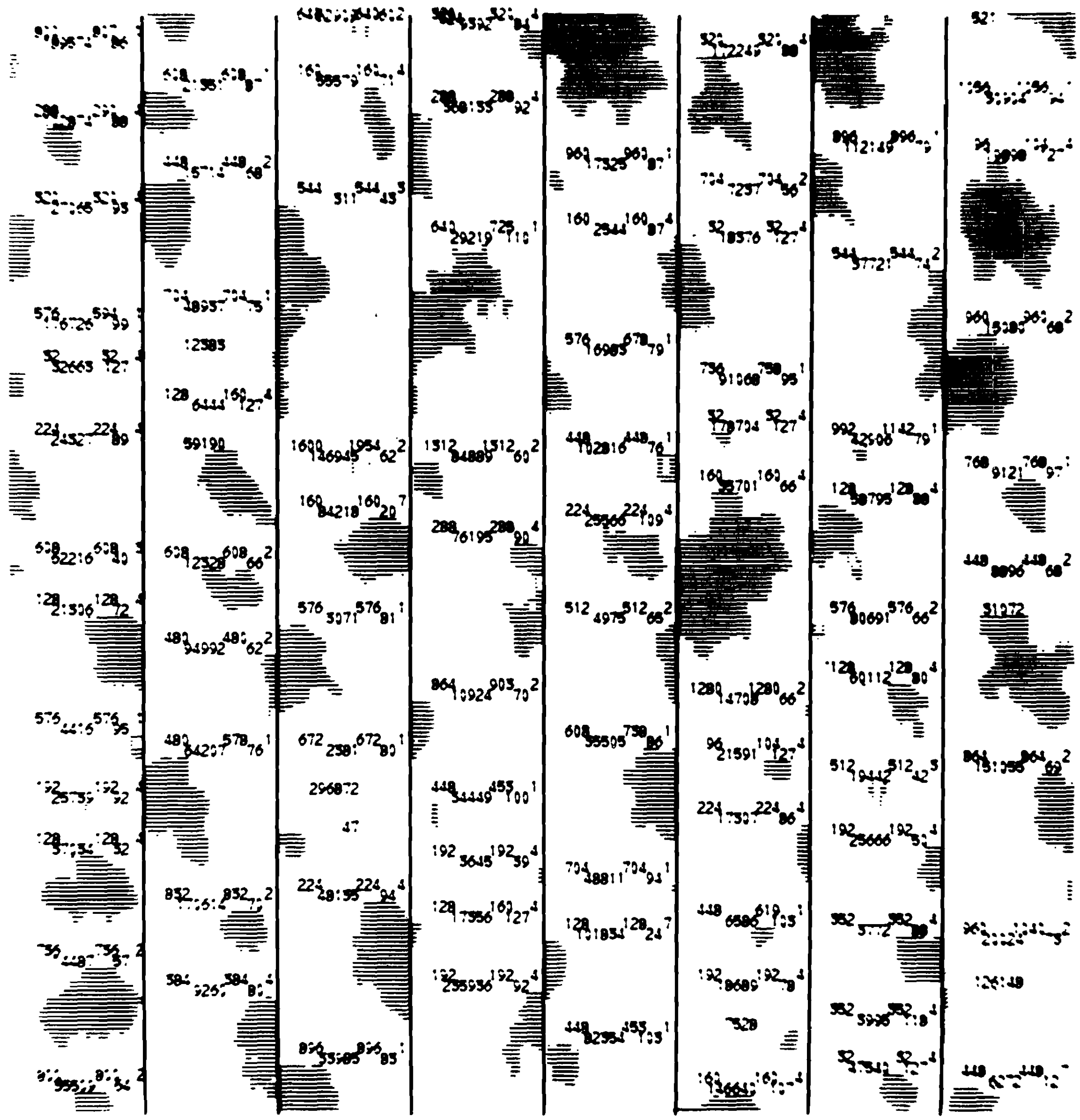

Fig. 20. Cloud particle images prior to passage through AgI plume in event 79-9 (1221:21-1221:27 MST 16 Mar. 1979). For increasing time read down from right to left.

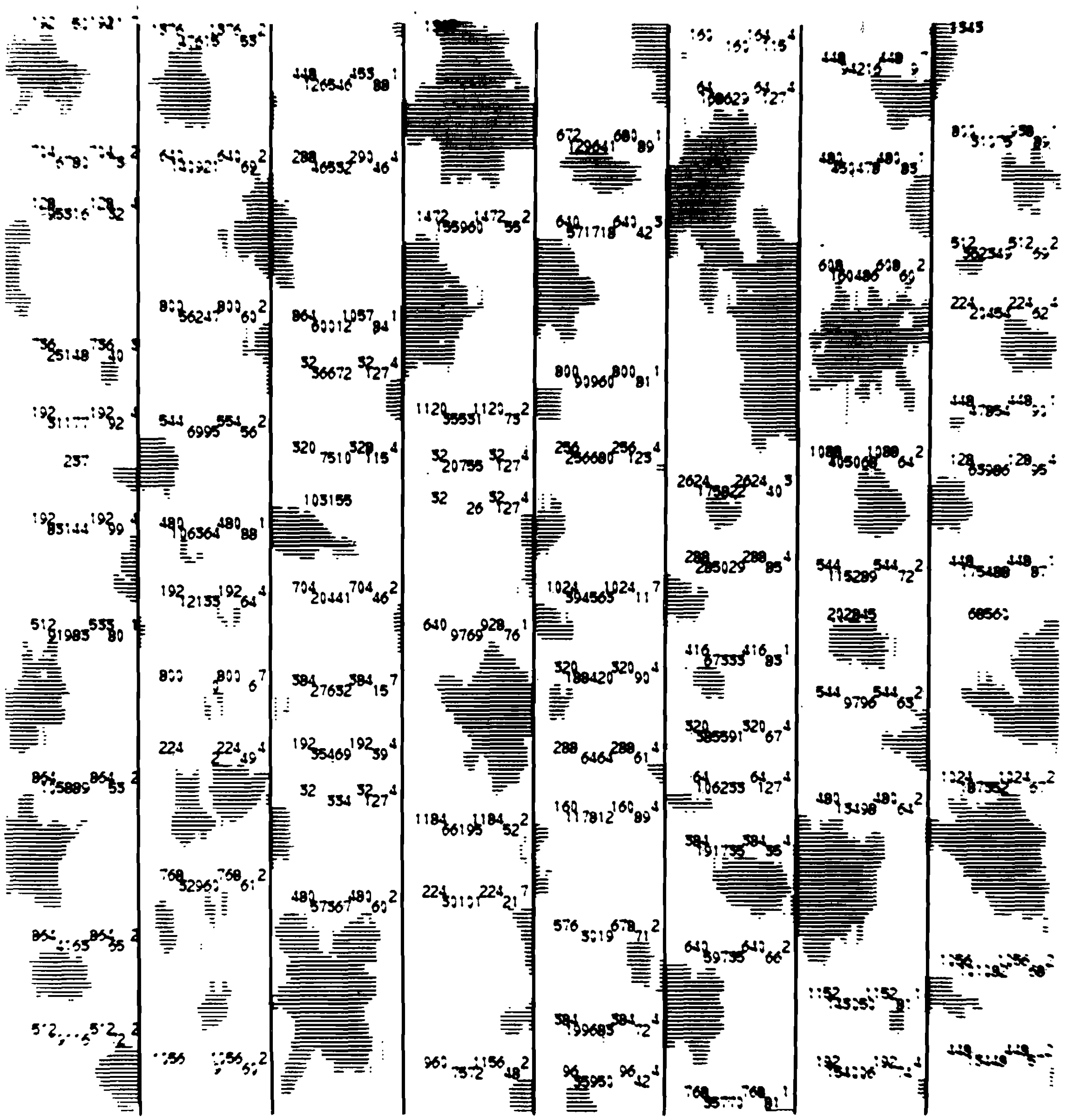

Fig. 21. Cloud particle images just prior to passage through AgI plume in event 79-9 (1229:43-1229:49 MST 16 Mar. 1979). For increasing time read down from right to left.

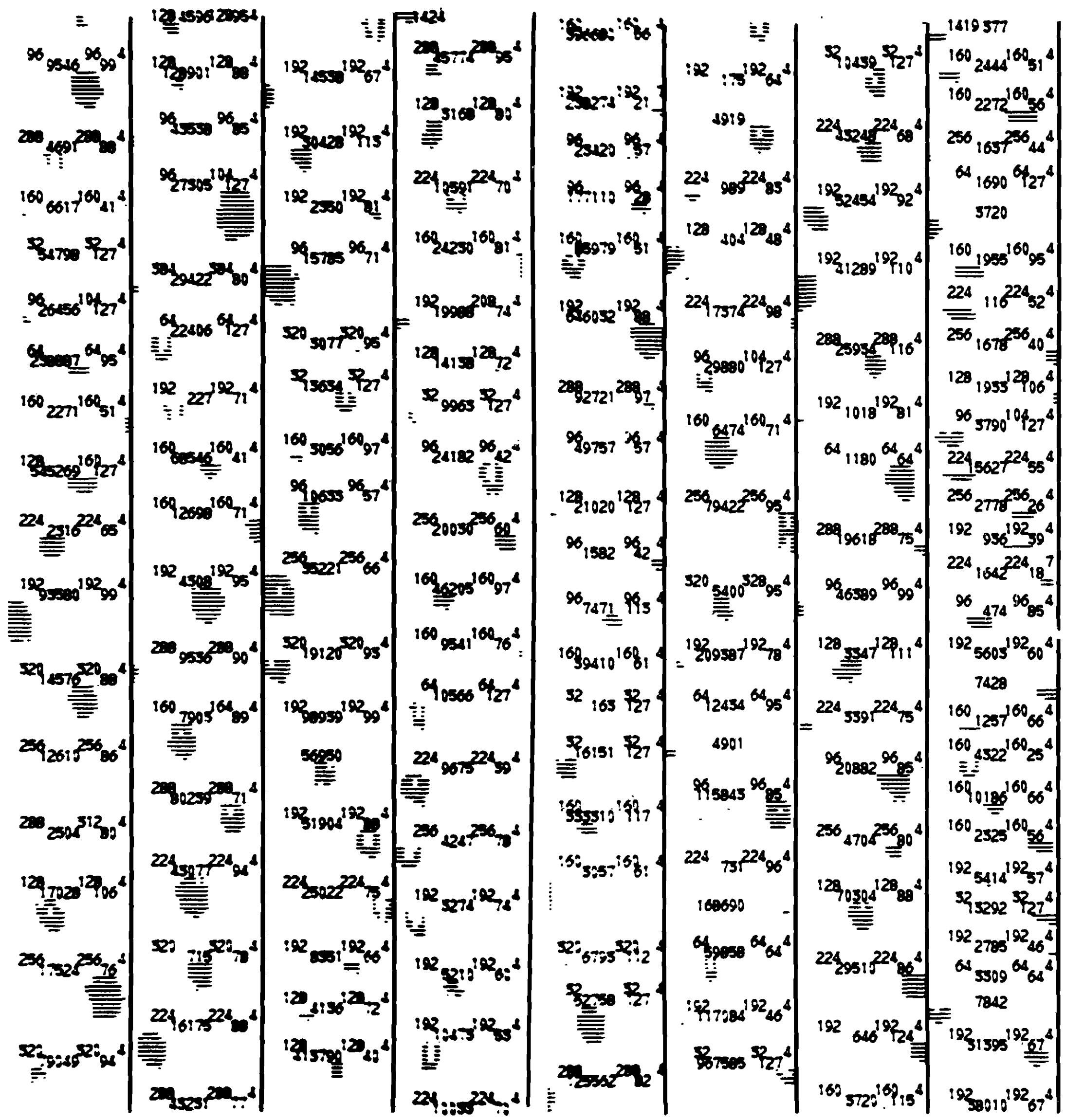

Fig. 22. Cloud particle images during passage through AgI plume in event 79-9 (1230:18-1230:26 MST 16 Mar. 1979). For increasing time read down from right to left.

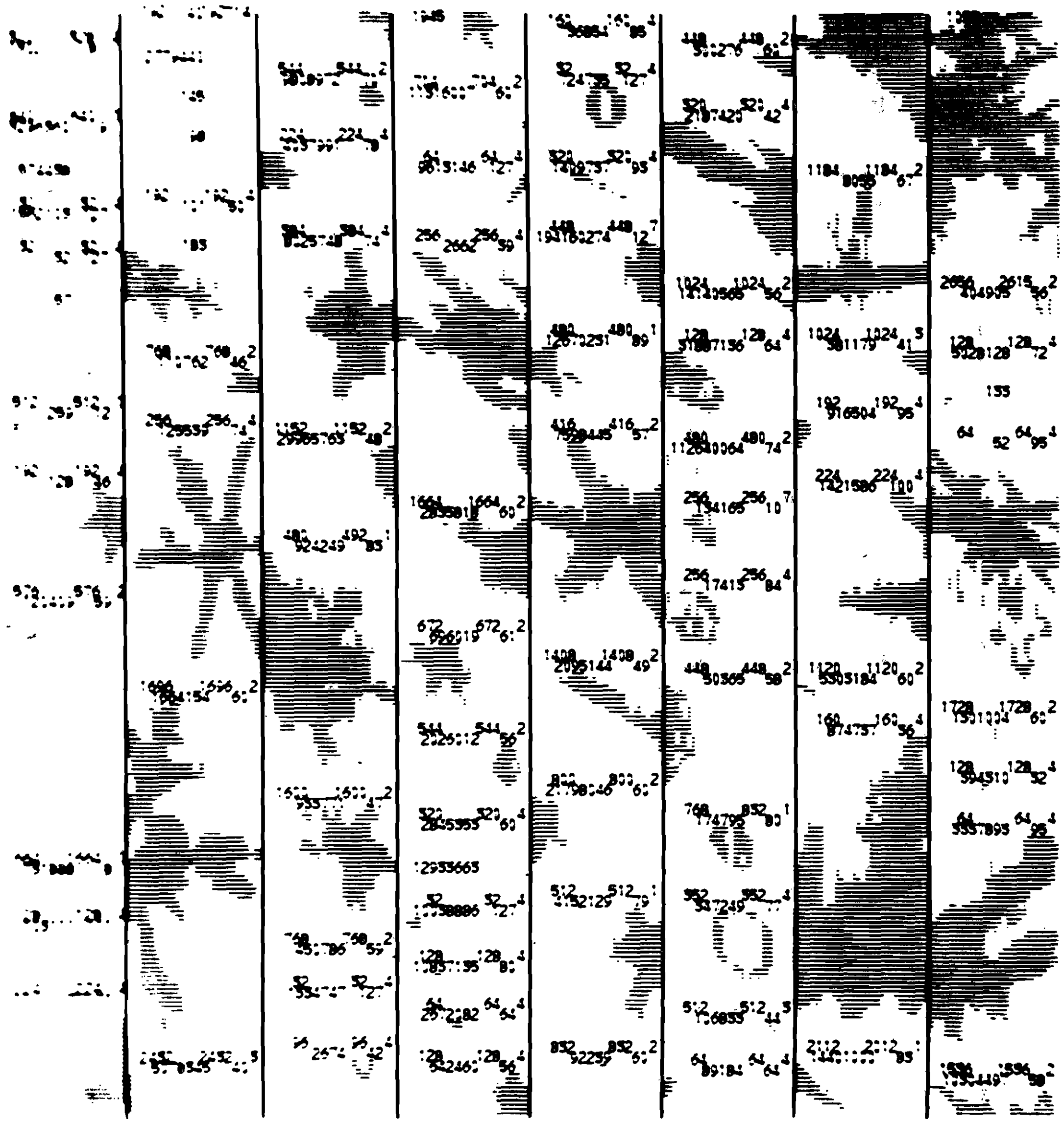

Fig. 23. Cloud particle images before, during and after AgI plume in event 79-10 (2226:55-2233:45 MST 16 Mar. 1979). For increasing time read down from right to left.

should result in the desired concentrations of ice crystals rather than an abundance of them. In fact, with the desired concentration of ice crystals, their size should increase fast enough so that they would be detected by the Mee ice particle counter.

5.6 Determination of cloud top temperature

5.6.1 Cloud top humidity formula. Visual reports from aircraft of cloud tops such as made by the cloud physics or seeding aircraft can be used along with vertical temperature profiles derived from rawinsondes to determine cloud top temperatures. The air temperature measurements aloft may be considered quite representative of the target area and of the duration of individual events because temperature at a given level changes relatively slowly in time and space compared to the full range of normal variation during the course of a winter.

On the other hand, such representativeness with humidity readings, to which cloud tops are directly related, does not exist. The humidity, or cloud patterns vary greatly in time and space. However, frequent (and closely spaced) measurements of humidity can be made by rawinsondes to overcome the high variability. In instances where cellular convection is present the use of rawinsondes is not practical to find the humidity field to determine cloud tops because of the very high spatial variability of clouds.

In most situations with winter orographic clouds the use of rawinsondes to collect humidity and temperature soundings adds valuable information concerning the cloud tops. What appears to be lacking is a clear cut basis for interpreting such data. While a useful formula for finding cloud tops has been given (Hill, 1973), other criteria based upon observations or subjective estimates continue in use. One reason for confusion is that some older observational studies were conducted when lithium chloride humidity elements in rawinsondes were in use. Thus cloud tops were present when the temperature dew point difference appeared to be greater than what was actually the case. Another reason for further uncertainty in applying formulas is that between 1965 and 1972 carbon humidity elements were not adequately shielded from solar radiation. But since 1972 rawinsonde humidity readings are believed to be much more accurate than previously. Consequently, the use of a physically derived formula has a much greater chance of yielding satisfactory results than previously. Problems with spatial and time representativeness still exist and attention must be given in interpreting the rawinsonde results.

The formula for determining the top of an ice cloud is based upon the following: The mathematical expression for ice saturation with respect to water, or the relative humidity at ice saturation, is well known. The formula, expressed as a relative humidity, is derived from an integration of the Clausius-Clapeyron equation. If the variation of latent heat with respect to temperature is neglected in the integration, the result is

$$r = \frac{e_{si}}{e_{sw}} = \frac{e_o \exp\left\{\frac{(T-T_o)\,L_i}{R_w T T_o}\right\}}{e_o \exp\left\{\frac{(T-T_o)\,L}{R_w T T_o}\right\}} , \qquad (1)$$

where r is the relative humidity, e_{si} and e_{sw} are the ice and water saturation vapor pressures, respectively, at temperature T; T_o is a base temperature (273K), e_o is the vapor pressure at T_o, R_w is the gas constant for water, and, L and L_i are the latent heat of condensation and sublimation, respectively.

This same relative humidity may be expressed in terms of vapor pressures over water at different temperatures, one at the dew point temperature T_D, the other at temperature T. This expression is

$$r = \frac{e_{swD}}{e_{sw}} = \frac{e_o \exp\left\{\frac{(T_D-T_o)\ L}{R_w T_D T_o}\right\}}{e_o \exp\left\{\frac{(T-T_D)\ L}{R_w T T_o}\right\}} \tag{2}$$

If the two relative humidities are equated then we find

$$\frac{(T-T_o)\ L_i}{T} = \frac{(T_D-T_o)\ L}{T_D} \ . \tag{3}$$

We now define $\Delta T = T-T_D$, where ΔT is the commonly known dew point depression. In particular ΔT_i is the dew point depression at ice saturation. After several algebraic manipulations, we obtain the formula

$$\Delta T_i = \frac{(T-T_o)\ (1-\frac{L}{L_i})}{\frac{T_o}{T} + (1-\frac{L}{L_i})} \tag{4}$$

This equation expresses the dew point depression between water and ice saturation.

To show the relationship described by Equation (4) ΔT_i versus temperature is shown in Fig. 24. This graph reveals the result that the dew point depression between water and ice saturation is nearly a <u>linear</u> function of temperature, and of course, independent of pressure.

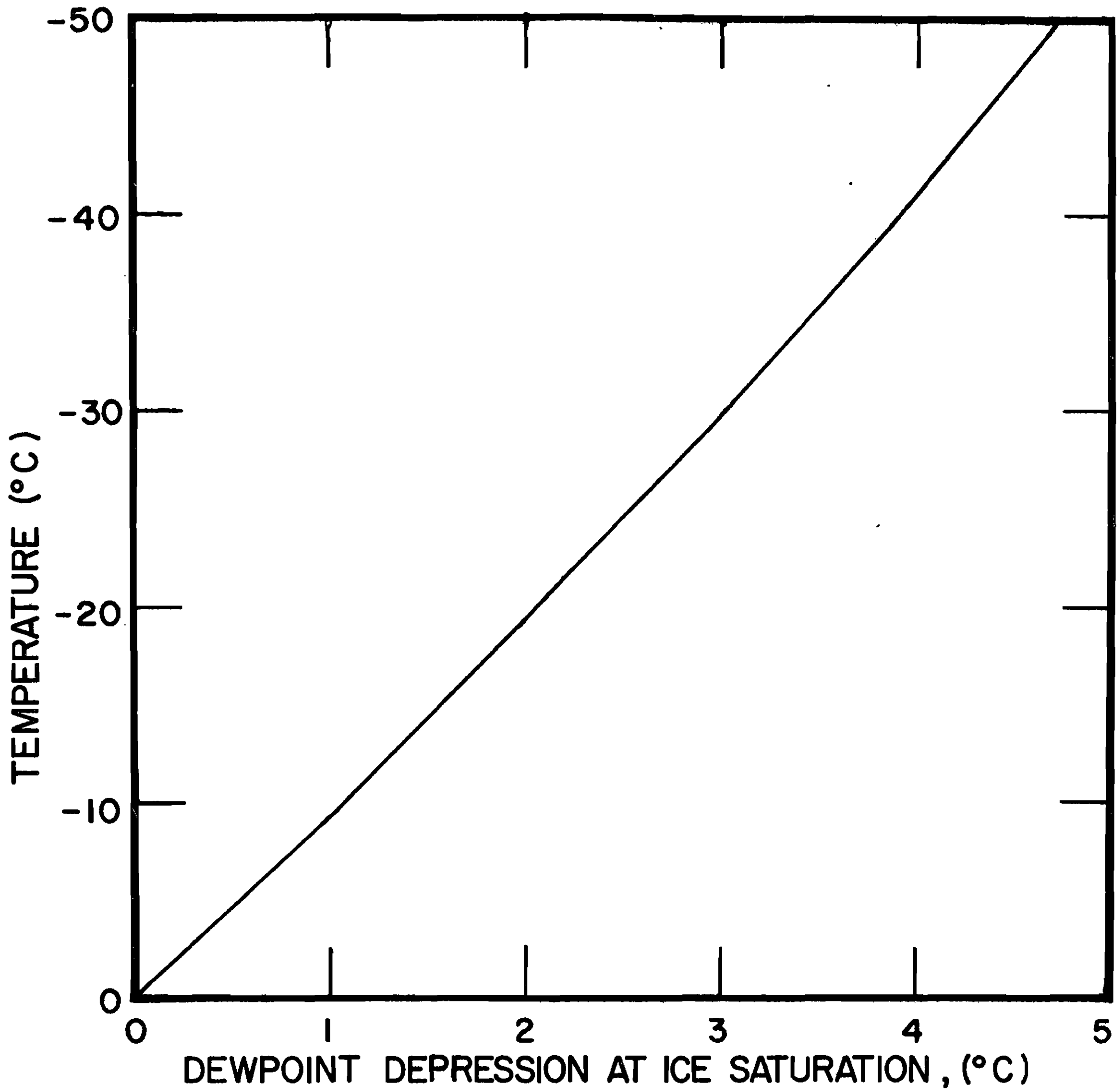

Fig. 24. Dew point depression at ice saturation versus temperature in degrees Celsius.

The chief virtue of Equation (4) is that a rawinsonde sounding may be inspected easily to check for appropriate observed ΔT_i's.

An approximation to (4) is simply

$$\Delta T_i = \Delta t_i \simeq 0.1 * t \tag{5}$$

where t is the temperature in Celsius. So a brief inspection of a rawinsonde plotted sounding is all that is required to find where Δt_i exceeds one-tenth of the temperature (^{o}C) as one proceeds upward. Some small amount of added temperature difference may be included in order to account for sounding errors such as may arise during calibration of the particular rawinsonde unit.

5.6.2 Representativeness of rawinsonde cloud top temperature. We return to the problem of representativeness of soundings. In the three winters of FY1974, 75 and 76 soundings were made at two hour intervals during some 44 events for a mountaintop cloud seeding experiment. Information derived from this study can be used to estimate cloud top temperature variability. In Fig. 25, cloud top temperatures at one time are plotted against cloud top temperature two hours later. The standard deviation of the two hour change is about 5^{o}C.

Similarly, in Fig. 26 the cloud top temperatures are plotted for a four hour change and in Fig. 27 for a six hour change. The standard deviations of cloud top temperature change are 13^{o}C and 22^{o}C, respectively. A graph of these standard deviations versus time is shown in Fig. 28. We may conclude that substantial changes in cloud top temperature occur over relatively short periods of time and that for purposes of determining cloud seeding potential soundings should be made at less than three hour intervals during periods when such a potential might be expected to exist.

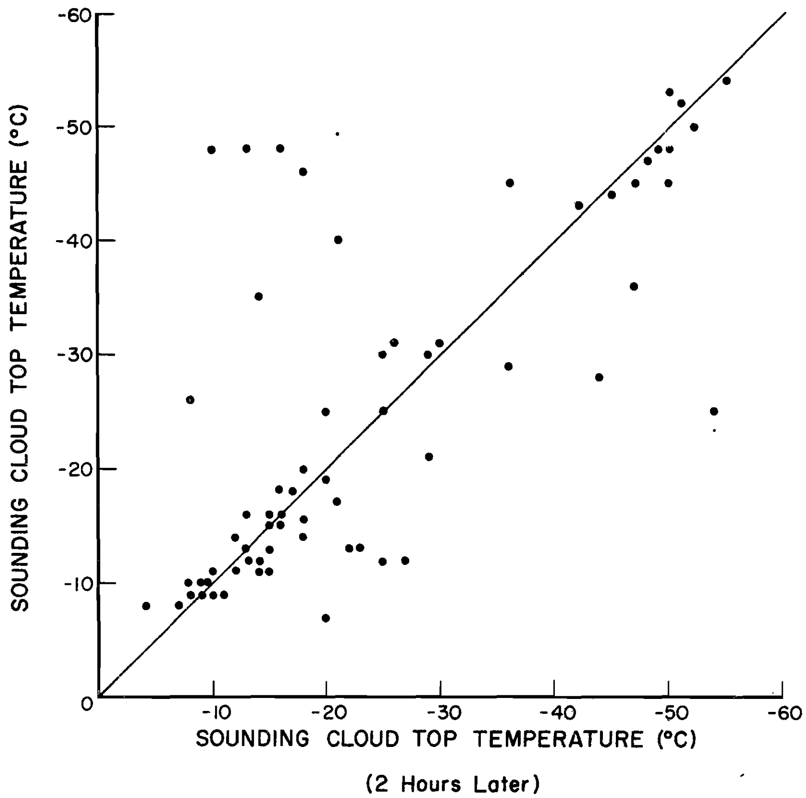

Fig. 25. Rawinsonde cloud top temperatures at successive two hour intervals.

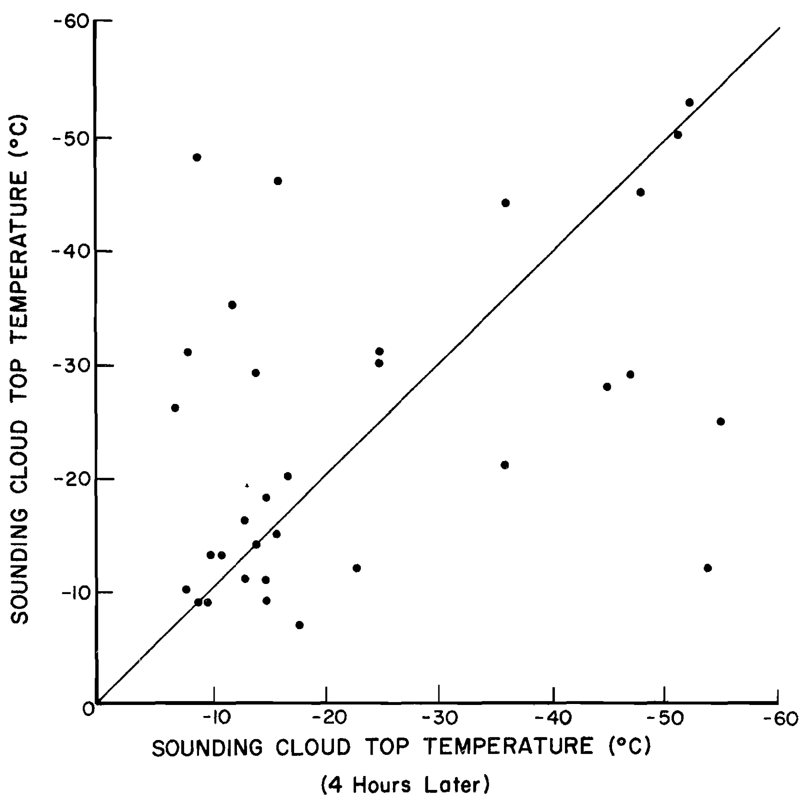

Fig. 26. Rawinsonde cloud top temperatures at successive four hour intervals.

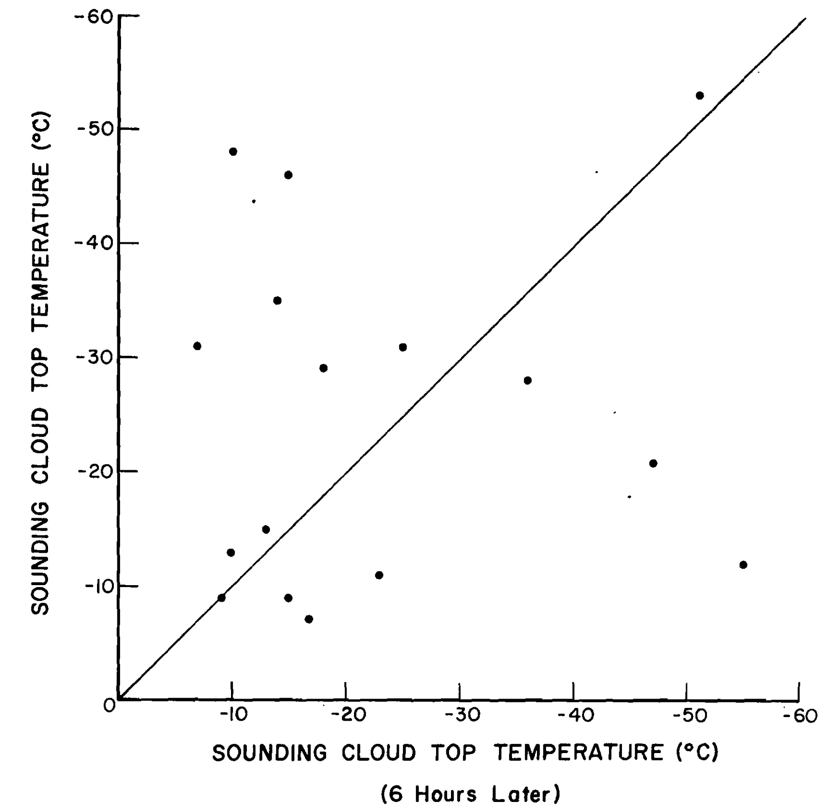

Fig. 27. Rawinsonde cloud top temperatures at successive six hour intervals.

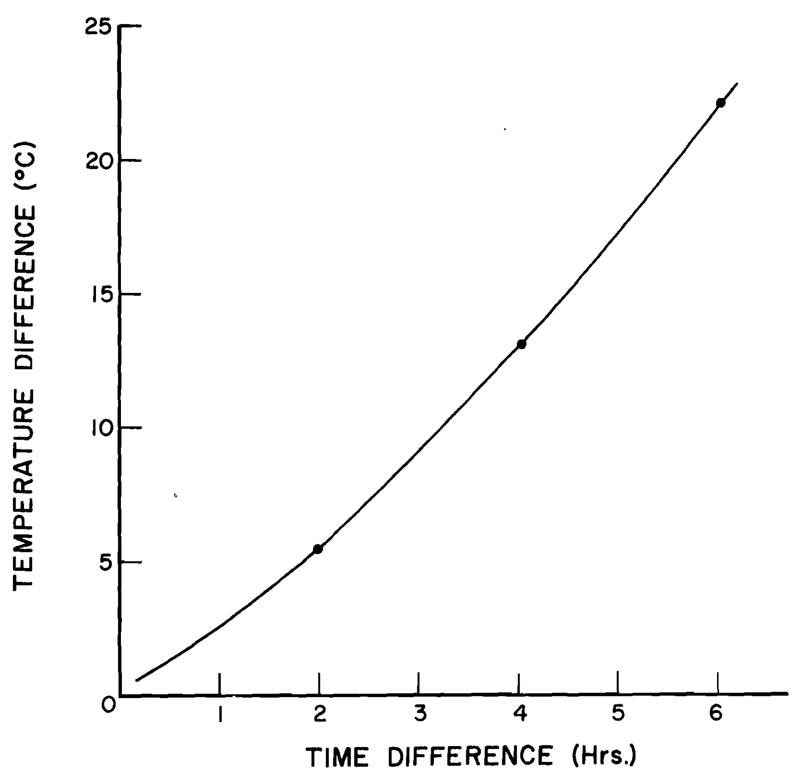

Fig. 28. Standard deviation of two hourly averages of cloud top temperature versus time difference.

In terms of spatial representativeness the time differences discussed above may be converted into spatial distances by assuming a typical speed of cloud movement. In this case we assume a cloud speed of 10 m s^{-1}. Therefore, three hours time is roughly equivalent to 111 km. So, rawinsonde soundings should be made at distances no greater than about 100 km along a mountain barrier where seeding is to be done. Of course, the expense of conducting such frequent and dense measurements is recognized, but the facts remain. Perhaps the use of a dedicated aircraft is not so expensive when the requirements of rawinsonde usage are taken fully into account.

5.7 Distribution of precipitation

5.7.1 Target to control precipitation relationships. In order to reduce the total effort and time required to detect seeding effects, such as might be found according to the seeding criteria put forth herein, it is extremely useful to invoke the use of covariates of target precipitation. The use of such data well correlated to target precipitation permits the accounting of a portion of the natural variability of precipitation and makes seeding effects more readily apparent than otherwise.

In general two types of covariates may be used. One is based on meteorological variables such as cloud depth and wind speed measured near the target area; the other is based on precipitation data measured in an area removed from the target. A combination of both types of covariates could also be used. Whichever set of covariates is used to account for natural variability of target precipitation, seeding must not modify the covariates. Otherwise, misleading results will be obtained.

Because our earlier results concerning the diffusion of seeding material indicate that seeding material should be released well upwind of the target area, the use of meteorological covariates near the target area is not appropriate. Data sufficiently far away must be used. Therefore, the likelihood of obtaining high correlations between target precipitation and the meteorological data is reduced according to the actual separation required. This is true also for precipitation data. However, as long as both types of covariate data must be obtained from locations away from the target area it is simpler and probably much less expensive to use precipitation data rather than other meteorological data.

For the foregoing reasons, we have obtained preliminary data on relationships between possible control area precipitation and target precipitation (for stations shown in Fig. 1). Correlations between the control and target stations are found for various sampling times in order to provide input to the selection of event duration. (The main criteria for the duration of seeded and unseeded events would be the normal duration of suitable seeding conditions.)

In any case the correlations for Swan Lake and Willard with each of the target area stations are shown in Figs. 29 and 30, respectively. Comparisons between target and control stations are made for the same time periods and no time lags are used in the present analysis. These correlations are based upon data collected between February 1 and April 15, 1979. With two hour event duration the correlation coefficient is generally lowest and increases as the event duration is longer.

These correlations may be regarded as a lower limit to what could be obtained if more stations were used in the control areas. Certainly there is an upper natural limit to what correlation could be achieved by the addition of more stations. But to get an idea of the improvement in the

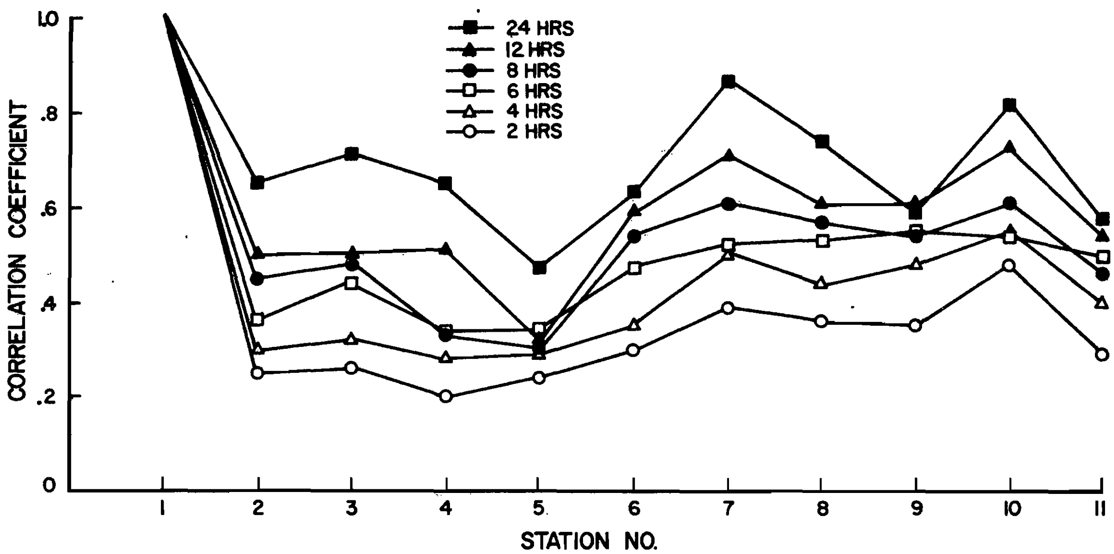

Fig. 29. Correlations for Swan Lake with each of the target area stations.

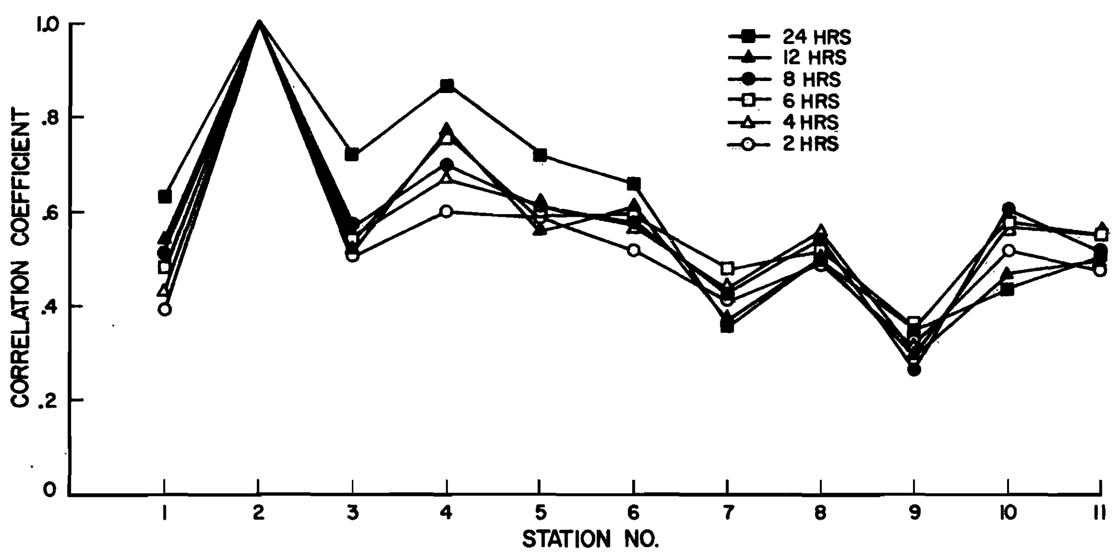

Fig. 30. Correlations for Willard with each of the target area stations.

correlations, we combine the two controls and correlate the average of these two with the average of successive pairs in the target area. The result is shown in Fig. 31. There is a substantial improvement in the correlations based upon two control stations and two target stations compared with one of each. The addition of a larger number of stations could reasonably be expected to yield still higher correlations. Thus with a target/control correlation of around 0.8 or 0.85 in individual events, the time required to detect a given seeding effect would only be about one-third of the time required otherwise, or in other words an experiment requiring as much as 12 years could be accomplished in 4 years with the use of such precipitation covariates. As an additional note, correlations of around 0.8 for individual events very likely translate to seasonal correlations in excess of 0.95, probably 0.98 or 0.99. Thus, the benefit of covariates to aid in detecting seeding effects becomes clearly evident.

5.7.2 Relationship of low to high altitude precipitation. In carrying out either operational or experimental cloud seeding projects, decisions concerning seeding opportunities, or assessment of meteorological conditions, must be made on the basis of available data. Such data include precipitation reports which are mainly from reporting stations at low elevations. Our point here is to examine the relationship between precipitation at low and high elevation stations, the latter being the target area and the location for which the seedability criteria apply.

To show the relationships of precipitation between the various stations, a matrix of correlations between individual stations is shown in Fig. 32 for event times of 6 hours. Correlations between individual

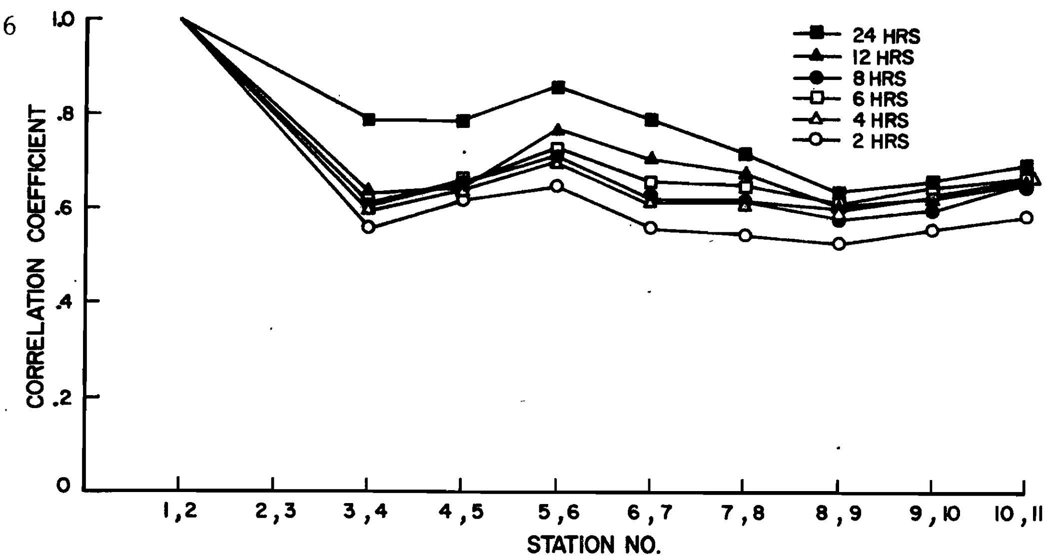

Fig. 31. Correlations for combined control stations with combined pairs of target area stations.

STATIONS	Swan Lake	Willard	UWRL	Cub R.	Richmond U.	Smithfield C.	Tony Grove L.	Tony Grove R.	Wood Camp	Sinks	Jebo
1 Swan Lake	1.00	.48	.27	.45	.30	.45	.48	.55	.49	.46	.50
2 Willard	.36	1.00	.51	.78	.59	.60	.44	.50	.24	.53	.64
3 UWRL	.44	.54	1.00	.81	.84	.37	.53	.54	.18	.46	.64
4 Cub River	.34	.76	.82	1.00	.74	.39	.38	.53	.29	.53	.50
5 Richmond Upper	.34	.59	.82	.81	1.00	.33	.27	.43	.18	.37	.55
6 Smithfield Canyon	.47	.59	.36	.41	.25	1.00	.77	.57	.50	.69	.65
7 Tony Grove Lake	.52	.48	.41	.41	.23	.74	1.00	.71	.64	.69	.66
8 Tony Grove Ranger	.53	.52	.28	.52	.39	.51	.67	1.00	.58	.73	.82
9 Wood Camp	.55	.35	.29	.37	.27	.53	.74	.62	1.00	.55	.60
10 Sinks	.54	.58	.52	.64	.41	.64	.69	.75	.49	1.00	.72
11 Jebo	.50	.55	.35	.53	.37	.53	.60	.81	.54	.69	1.00

Fig. 32. Matrix of correlations for 6 hour event times for individual stations. Box enclosing 9 values refers to low altitude stations; box enclosing 18 values refers to high altitude stations.

stations in Cache Valley average about 0.8. On the other hand correlations between valley stations and those in the target area at high elevations are typically only around 0.40. Thus, it is clear that precipitation at high elevations is poorly represented by precipitation at nearby low elevation stations.

We can infer that if precipitation at high elevations is not well represented by low elevation precipitation, then the presence of clouds with abundant supercooled water is even less well represented. Therefore, the practice of restricting seeding to typical storms associated with low pressure systems and fronts may well lead to missed opportunities. As we have already found, the best seeding opportunities are associated with situations with little or no precipitation over the target area, normally located at high elevations with winter orographic clouds. Although low pressure systems and fronts may be required to transport adequate moisture into the target region, these meteorological systems are not generally well suited for seeding. It is more likely during times when moist flow exists without the normally heavy precipitation associated with storms that the best seeding opportunities are present.

As an example we refer to event 79-2, in which case a cold front had passed through the area many hours before, yet the cloud physics aircraft picked up over 8 cm of ice in less than an hour. Such great amounts of supercooled water passing over the mountain at a speed of some 20 m s^{-1} represents a large potential snowfall, perhaps as much as several percent of the season's amount. Yet the weather charts showed little activity in terms of winter storminess.

6.0 PROPOSED PLAN FOR ACHIEVEMENT OF IMPROVED CLOUD SEEDING TECHNOLOGY

6.1 Verification of current findings

Because our current findings reveal a set of criteria for seeding opportunity recognition based upon in-cloud physical measurements as well as precipitation data, it appears that further substantiation of the findings should warrant a considerable priority as far as the improvement of cloud seeding technology is concerned. To do this the airborne portion of the research could be accomplished merely by making in-cloud supercooled water measurements. Other parameters upon which the criteria are based can be obtained from ground based instrumentation. Furthermore, only one season of data collection would likely be required, because in the previous three years a large amount of effort was directed in exploratory research. It is the results of these explorations that have led to our current position. Thus, in the immediate future a much more focused effort would be made to refute or substantiate our current findings. Only if our next period of data collection is particularly devoid of suitable seeding opportunities would a second year of such data be required.

6.2 Climatology of supercooled water

Another aspect of developing seeding technology is the documentation of how often and under what general meteorological conditions supercooled water is found in abundance. Development of suitable instrumentation is underway to accomplish this task. When such data are available, it will be possible to estimate just what potential benefit does exist. Our present thinking is that a 30 percent increase in winter precipitation could be obtained if cloud seeding technology were fully exploited. This amount is based upon our current limited knowledge of the frequency of clouds containing supercooled water in large amounts.

6.3 Seeding to increase precipitation

Whether a given opportunity for increasing precipitation by seeding is actually realized depends greatly upon what seeding material is used and how it is delivered. Seeding from ground generators is limited by the presence of low level inversions and by the great variability of airflow at low elevations. Also, the activation of silver iodide at low elevations where the temperature is relatively warm is often insufficient to stimulate precipitation. On the other hand we have found that airborne seeding is greatly limited by the weak diffusion generally found in winter orographic clouds. Only if airborne released silver iodide is released far upwind is there sufficient diffusion. However, timing and targeting problems become more acute.

At least two possibilities exist for overcoming some of the difficulties associated with delivery. One is to base seeding generators on top of mountains. This was done in previous UWRL experiments, and in fact it was the mountaintop seeding rather than the airborne seeding that showed seeding effects--related to the presence of substantial supercooled water (Hill, 1979).

A second alternative is to use dry ice released from a jet aircraft flying at high altitude, say 20,000 ft. With dry ice falling through the clouds just the supercooled water will be affected--as desired. Lack of vertical diffusion will not be a problem because the dry ice falls through the clouds. Weak horizontal diffusion is overcome somewhat by the much higher traverse rate of a jet aircraft, and partly by seeding further upwind than is presently done. Therefore, our inclination is to utilize a jet aircraft for delivering dry ice into clouds upwind of the target area. It is also noted that with dry ice there is much less chance of undesired seeding downwind as with silver iodide, because the latter becomes more and more active as ice nuclei as it diffuses to higher altitudes and colder temperatures. Developing and testing such a seeding strategy would probably take one or two seasons to accomplish.

6.4 Evaluation of improved cloud seeding technology

As previously described the use of control precipitation areas with known relationships to the target area will greatly reduce the time required to evaluate any effects of cloud seeding. In the forthcoming year we expect to complete our analysis of possible control configurations. We expect the control areas to be further away from the target area than as at present. Correlations between target and control area precipitation are expected to be around 0.8 or 0.85. Precipitation measurements will likely be made using new digital type weighing gages with solid state memory.

6.5 Concluding statement

Inasmuch as we are developing an improved cloud seeding technology it is important to distinguish what we are doing from existing cloud seeding programs to increase precipitation in Utah. These programs are based upon cloud seeding technology developed in the past. Although this technology has proved useful, there is little question that substantial improvements can be made. Present plans to evaluate these programs experimentally are both useful and needed. At the same time development of improved cloud seeding technology is needed. Such development has been underway at UWRL over the past three years. Presently, another season of data collection is required in order to obtain additional information on in-cloud supercooled water content and how it relates to other parameters. Final development of seeding strategy and refinement of evaluation technique are also needed. When these tasks are completed, it would then be appropriate to carry out a longer term program to fully test the precipitation augmentation by seeding according to the improved technology. The present estimate of time required for this phase of the work is three to five years, but a better estimate will be possible at the end of the development phase.

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