DELIVERY OF NUCLEATING MATERIALS TO CLOUD SYSTEMS FROM INDIVIDUAL GROUND GENERATORS

Presented
to the

Bureau of Reclamation
Third Skywater Conference on the

Production and Delivery of Cloud Nucleating Materials

February 14-16, 1968

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Delivery of nucleating materials to cloud systems from individual ground generators can play an important role in the beneficial modification of orographic cloud systems. Substantial evidence from the Colorado State University mountain study at Climax is presented to show that ground-released seeding materials do under some weather situations in fact enter the mountain cloud systems and produce changes in the precipitation. Evidence is also presented to show that under other weather situations seeding materials are not carried to the proper clouds at a place and time to be of value.

A discussion of atmospheric transport mechanisms is presented to serve as a basis for understanding the motions of seeding materials once released from a ground source. The approaches, or directions, for further research are discussed. This includes consideration of the coagulation problem in the vicinity of the generator site. The use of wind tunnel modeling, which can provide basic information and specific results for specific areas, is emphasized.

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I. Introduction

The production of effective seeding materials in quantities required for cloud modification is clearly feasible. The efficiency and concentrations of materials produced can be tested in the laboratory under conditions that reasonably simulate those occurring within cloud systems. Research in progress should provide even more efficient nucleating material and systems for their production.

The delivery of seeding materials to the desired location in clouds, at the right time, and in the proper concentration is more complex than the production of the seeding material itself. Many methods of delivering seeding materials have been employed. These include the use of aircraft, balloons, rockets and rising air currents. The topic we have been asked to discuss concerns the delivery of the materials from a ground source. This infers the delivery of the seeding materials by rising air currents in which the cloud is forming.

This frequently requires the release of the materials at considerable distances from the desired location in the cloud. Complexities of both large and local scale horizontal airflow seriously complicate the problem. The vertical component of airflow available for transporting the material aloft presents the greatest problem since it is not readily observable. Changes in the nucleating characteristics of the seeding materials during transit serves as a further complication.

On the other hand certain technical advantages can accrue with ground seeding. For one, the distance between the source and cloud can allow for desired dilutions of the seeding materials from some 10^{12} to 10^{14}/sec at the release site to desired in-cloud concentrations of some 10^4 to $10^5/m^3$. Ground seeding under some circumstances can also permit the accumulation and storage of seeding materials in the lower layer of the atmosphere over an extensive area. This storage of materials can then be available to an extensive volume of the atmosphere when proper cloud conditions develop and the associated vertical flow is available for their upward transport.

Section II below presents evidence that effective delivery of seeding materials from ground generators has been successfully accomplished under some weather conditions in the Climax orographic seeding experiment. Evidence in Section III shows that seeding materials are not being adequately transported in desired concentrations to proper locations in the cloud system under other weather situations. General comments on the problem are presented. This includes a discussion of transport mechanisms in the atmosphere and comments on approaches leading to a better understanding of the delivery of ground-released seeding materials.

Requirements, or needs, for ground seeding were discussed (Grant, 1967) at the Second Skywater Conference and will not be presented here.

Space does not permit detailed descriptions of the equipment and procedures used in obtaining data presented below. Most of this is available in the literature (Grant and Schleusener, 1961; Grant and Mielke, 1965; Grant, Chappell and Mielke, 1968; Reinking and Grant, 1967; Reinking and Grant, 1968; Furman, 1967; Hindman and Rinker, 1967; Hindman, 1967; Grant, 1963).

II. Evidence that seeding materials are transported to cloud systems under some weather conditions

It is clear that materials are advected into the Climax target area under some weather situations.

A. Evidence for low level transport of seeding materials

1. Increase in ice nuclei concentrations at target area ice nuclei counters

Seeding materials are consistently observed at ground stations in the Climax target area when released many miles upwind. Increases in ice nuclei concentrations (related to seeding activities) have been observed in 67% of the seeded cases at an ice nuclei observing station at the High Altitude Observatory (Grant and Mielke, 1965). The mean concentration on randomly seeded days has been $12/\ell$ while the mean on randomly selected unseeded days has been $2.7/\ell$. The difference is statistically significant at the 1% confidence level. Reinking and Grant (1967) have carried out a selective study of ice nuclei concentrations on seeded and non-seeded days for cases when no other known seeding had occurred during the five days preceding seeding decisions at Climax. For the 51 cases available they also find that seeding effects could be observed at the HAO site on 67% of the days. Detection was uncertain on 17% of the days while only 16% of the days had clearly not been affected. The number of cases falling into the respective categories are shown in Figure 1 for a range of concentrations observed.

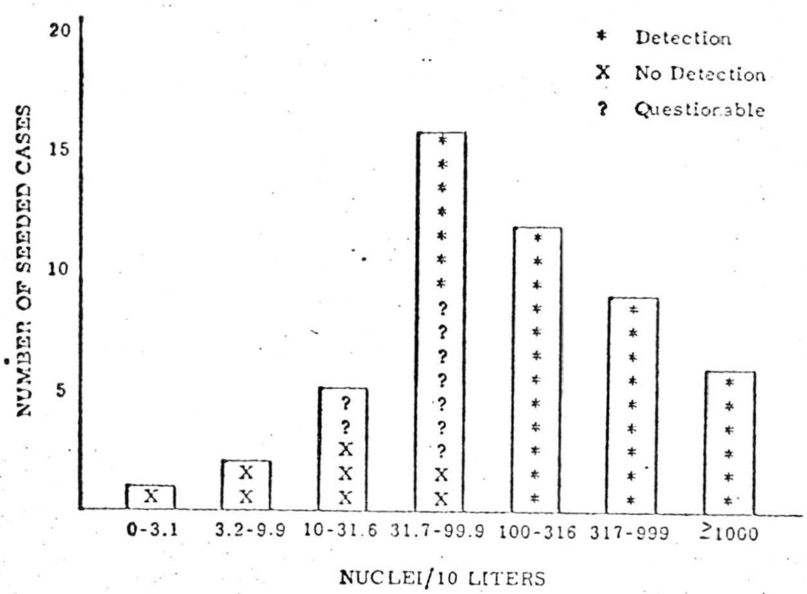

Figure 1. Frequency of concentration levels attained by ice nuclei activated at -20° C on seeded days at Climax, Colorado. Detection of seeding material is indicated for individual cases.

2. Seeding materials in transit are not critically affected by ultra-violet deactivation.

The low level transport of the seeding materials has not been critically affected by in-transit losses, through coagulation, U. V. decay, or collection by precipitation. Figure 2 shows the concentrations of ice nuclei preceding, following and during a seeding event on May 12, 1967. Seeding generators operated were 8 to 20 miles upwind. It can be readily noted that background concentration effective at -20° C were around 1/liter both preceding and following the seeded event during which concentrations increased to values ranging from 20 to 200/liter. While no observations were taken during midday, U. V. exposure at the 0900 observation time is substantial during May at the latitude of Colorado. Many daytime observations of ice nuclei concentrations of the same general magnitude as nighttime observations are available from Climax during the winter months.

Few observations have been taken during daytime hours during the summer. These do show lower concentrations than would be expected, but as shown by the May 12 case still frequently show high concentrations of ice nuclei associated with seeding. Both U. V. deactivation and increased convection in the lower levels of the atmosphere could reduce ice nuclei concentrations observed at Climax during the daytime summer hours.

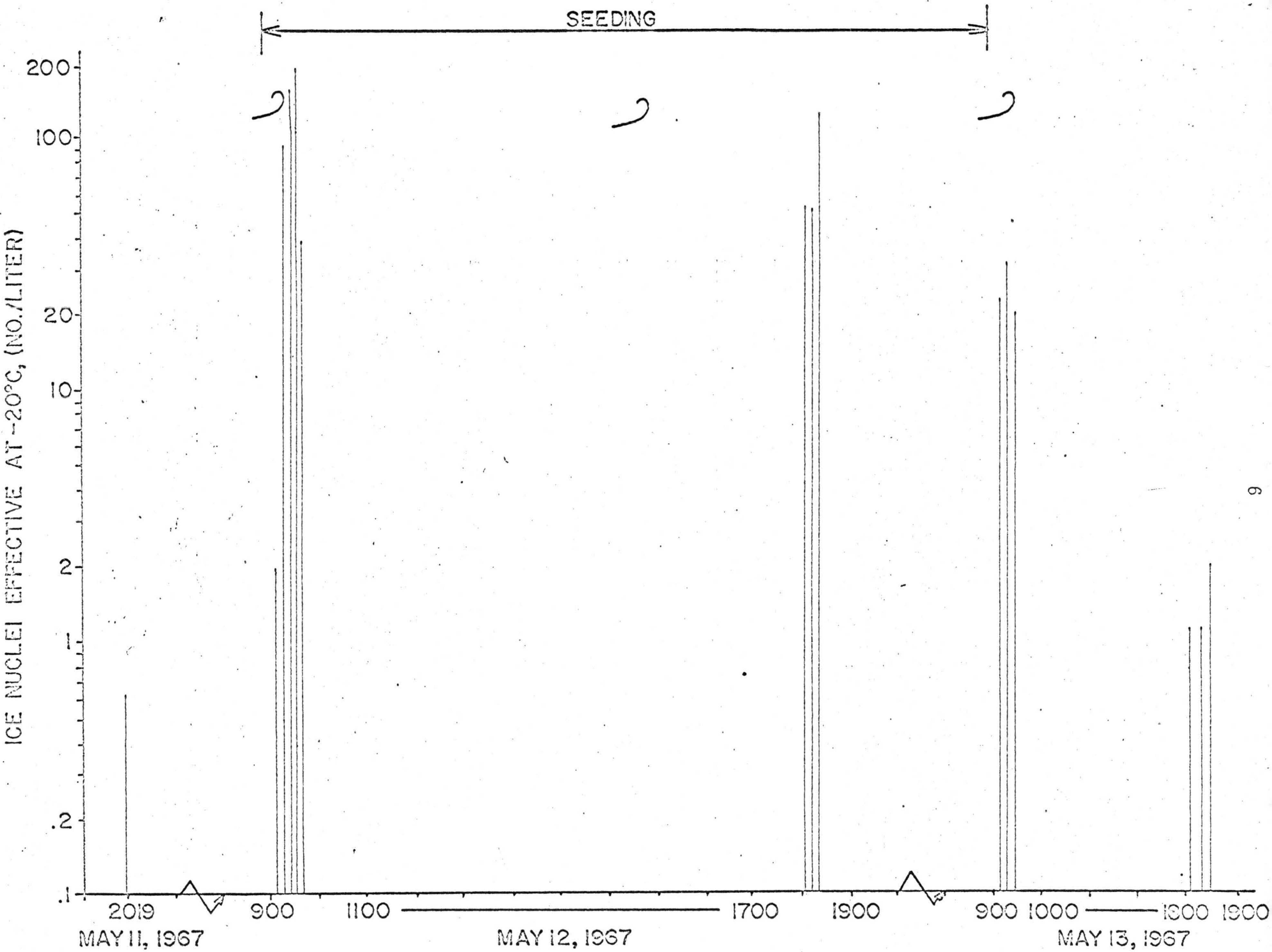

Figure 2. Change in ice nuclei concentrations at Climax after seeding at upwind ground site under clear sunny skies

3. Seeding materials in transit are not critically affected by collection by falling precipitation.

Figure 3 is one of a number of cases available that indicate the losses of seeding material to collection by snowfall are not critical during the transit time experienced in the Climax experiment.

As in other examples presented above it can be noted that concentrations of ice nuclei active at -20° C prior to and following the seeding period of 29 and 30 December 1961 were a few per liter. Moderate snowfall had been falling for several hours before the randomly selected seeding interval started on the morning of 29 December. Despite the continuous and general snowfall during the seeding period ice nuclei concentrations increased from 10 to nearly 400/liter during the seeding period--concentrations of the same order of magnitude as observed on other seeded days and intervals not experiencing such extensive snowfall. Figure 4 demonstrates the same effect for the 25-27 February 1961 period. Hourly precipitation is shown for the period when ice nuclei concentrations increased during the seeded interval. While this shows clearly that seeding material does survive transit through such snowfall, analyses of data are in progress to see if the magnitude of the losses which do occur can be established.

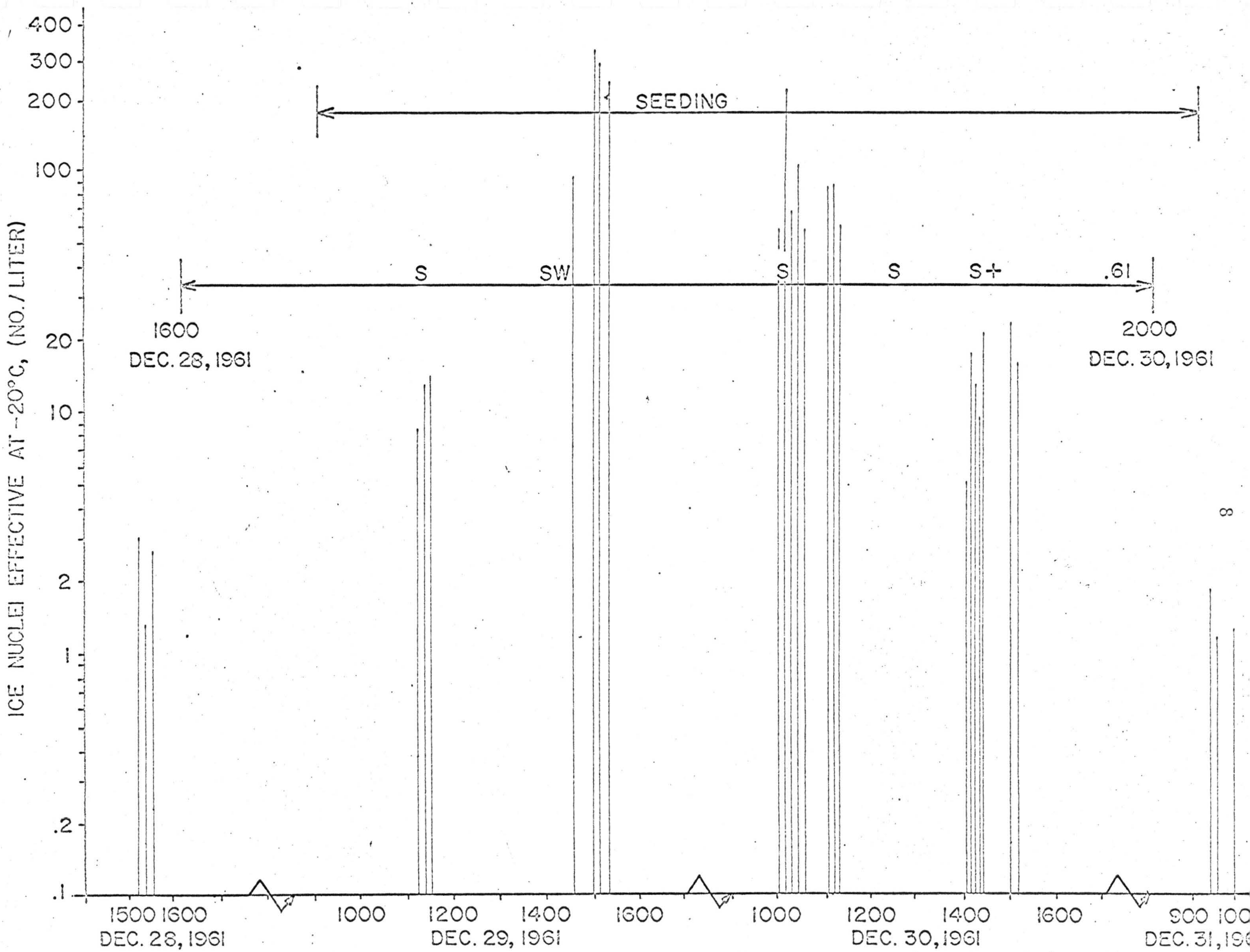

Figure 3. Change in ice nuclei concentration at Climax after seeding at upwind

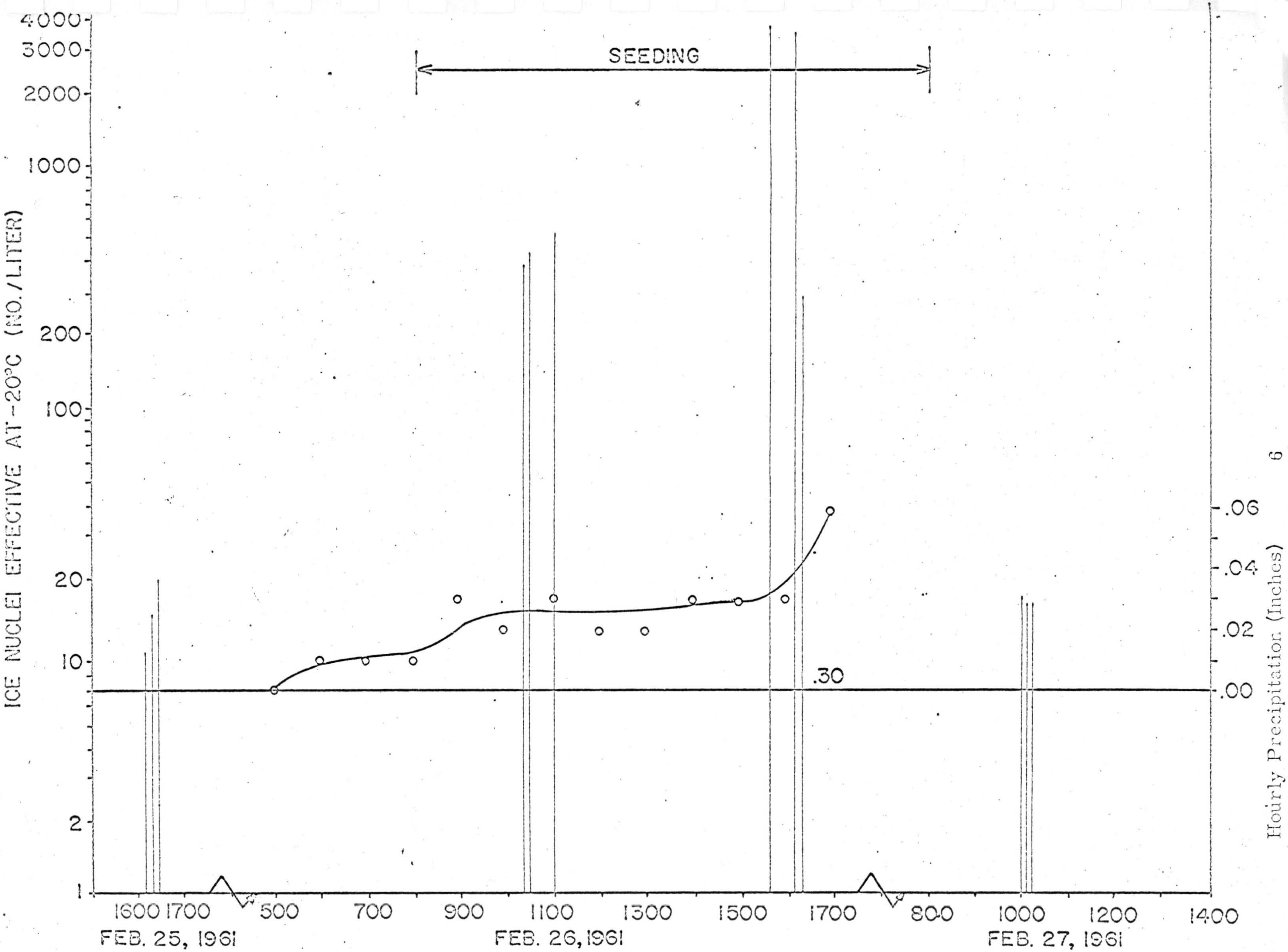

Figure 4. Change in ice nuclei concentration at Climax after seeding at upwind ground sites when moderate and heavy snowfall is ...

B. Evidence for the vertical movement for seeding materials from the surface layers

A substantial body of evidence is available to show that artificial ice nuclei advected to the target area under some circumstances are also transported vertically into the overlying cloud systems. Visible smokes and no-lift balloons can frequently be used to demonstrate this.

1. Movement of seeding materials into overlying clouds

Changes in concentrations of ice nuclei observed at the surface can frequently be used to infer this vertical movement. Figure 5 shows a case observed by myself and Vincent Schaefer on 7 February 1962. Background concentrations of natural ice nuclei were around 1/liter before and after the randomly selected seeded day of 7 February. Concentrations of ice nuclei increased in association with the seeding with high (40 to 140/liter) surface concentrations centered around 0930, 1330, 1515, and 2015. On this day small convective cells were passing the observing station. The main passage of such cells is represented by a sketch of a cumulus cloud at the appropriate time. It can be noted that with the approach and passage of each of these convective areas that the surface concentration of ice nuclei decreased. It is assumed that high concentrations of artificial nuclei in the surface layers were carried aloft into these cloud systems.

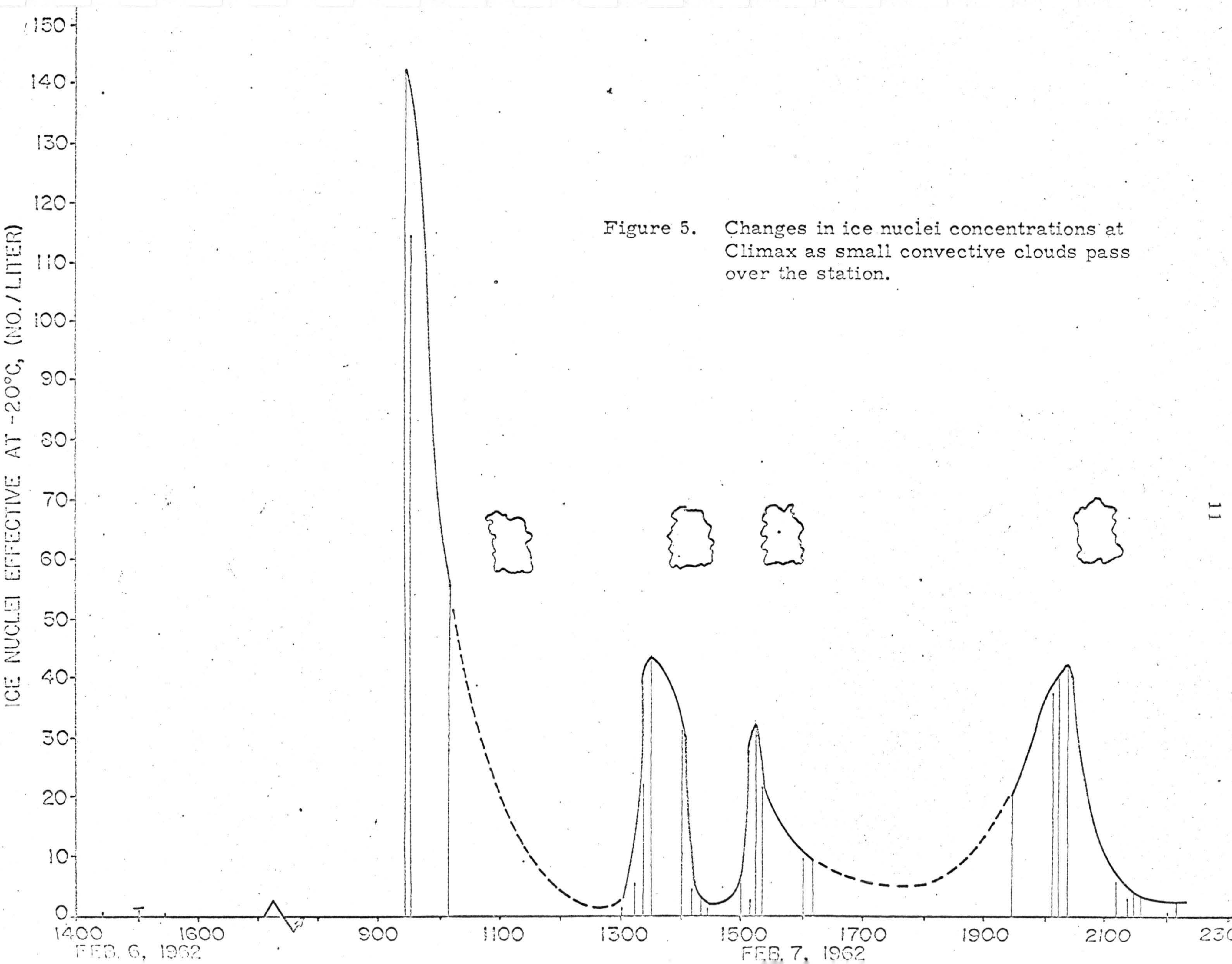

Figure 5. Changes in ice nuclei concentrations at Climax as small convective clouds pass over the station.

2. Movement of seeding materials from lower to higher elevation ice nuclei observing sites

This same effect can be noted with reference to Figure 6. The sharp increase in ice nuclei concentrations observed at HAO on 21 December 1967 were not in general reflected at the higher elevation station at Chalk Mountain indicating that during most of the interval seeding materials were not being transported vertically from the surface layers. However, during short bursts around noon substantial increases in concentration were observed for short intervals at the Chalk Mountain site indicating that vertical transport was taking place during these intervals. It is also interesting to note that, as in the 7 February case sited above, substantial lowering of concentrations at the lower elevation site at HAO occurring almost simultaneously.

3. Detection of seeding material above the mountain site from a kite system

Efforts are being extended to the detection of the increase in ice nuclei concentrations within the cloud system above the mountain peak using a large kite system. Presently, samples are being taken on seeded and non-seeded days at varying elevations. The present system requires the analysis in the ground station of a sample of air captured from this within the cloud. This is a slow process and a

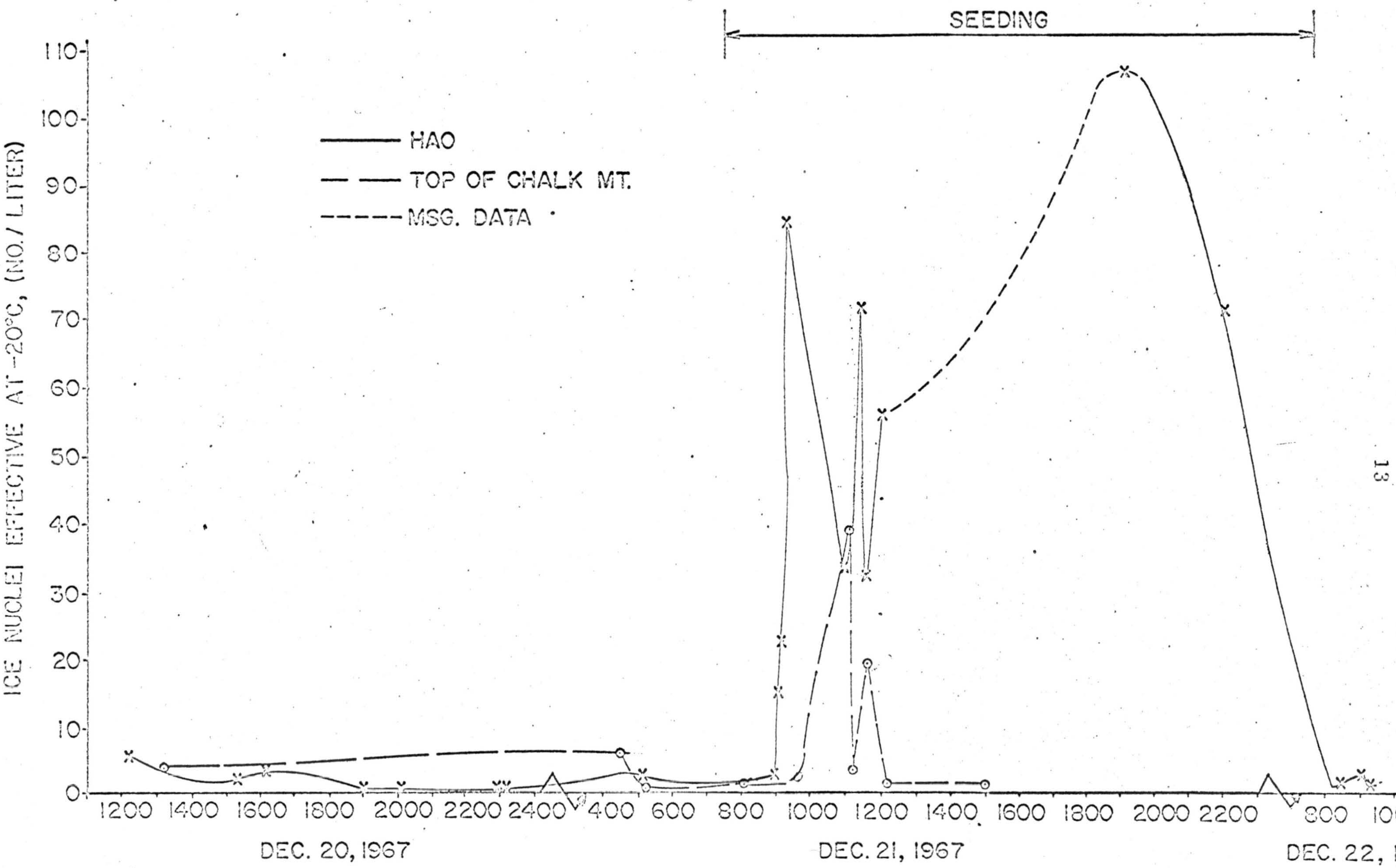

Figure 6. Changes in ice nuclei concentrations at Climax (11,300 ft msl) and a higher station on Chalk Mountain (12,000 ft msl).

13

continuous system of sampling is being developed. Even though the present sample of data is limited, increases in ice nuclei concentration to 10 to 100/liter have been observed during seeding episodes at elevations several thousand feet above the mountain peak and at an elevation where the orographic precipitation commonly forms.

C. Indirect evidence of presence of seeding by their action in cloud systems

Evidence for the presence of the seeding materials in the cloud systems can frequently be found by noting changes in the visually observed cloud features, in the concentration of snow crystals falling from the clouds, in changes in the precipitation associated with seeding, and in the silver content of falling snow.

1. Visually observed changes in seeded clouds

Visual observations of clouds in the seeded area that are "iced out" in relation to out-of-plume clouds are not commonly observed at Climax due to the extensive orographic cloudiness during good seeding events. They are, however, frequently observed on days with more scattered clouds. Such observations have been observed in many seeded cases but do not provide a very quantitative measure of the presence of the seeding materials in the cloud system.

2. Differences in concentrations of ice crystals falling from seeded and non-seeded clouds

Observations of concentrations, sizes, and shapes of ice crystals falling from the mountain clouds on both seeded and non-seeded days provide a more quantitative index of the effect of the seeding materials in the cloud system. A substantial number of cases are now available that show increases in cloud ice crystal concentrations that correspond to increases in ground-measured ice nuclei concentrations. The reduction of ice crystal data for a portion of the available observations is now nearing completion. In approximately half of the cases thus far reduced, ice crystal concentrations are much lower than surface-observed ice nuclei concentrations (Grant, 1968). Even in these cases, however, ice crystal concentrations are an average factor of 3 greater than a sample of the average ice crystal concentrations for the unseeded cases. In the other half of the cases ice crystal concentrations are of the same order of magnitude as the increased ground-measured ice nuclei concentrations resulting from seeding. The ice nuclei concentrations in these cases are 1 to 2 orders of magnitude greater than those on non-seeded days.

3. Differences in precipitation between seeded and non-seeded days

Differences in precipitation between seeded and non-seeded days also provide evidence that the seeding material released from the ground has in fact entered appropriate locations in the cloud system. Analyses (Grant and Mielke, 1965; Grant, Chappell, and Mielke, 1968) indicate that, under certain meteorological conditions, precipitation has been changed on the randomly seeded days in comparison to that on non-seeded days. Table I, after Chappell (1967), shows the indicated change in precipitation for a variety of meteorological stratifications. It also shows the probability that these changes could have occurred by chance. It can be noted that the probability of precipitation difference between seed and non-seeded events occurring by chance is very low for certain meteorological stratifications. Particularly striking are the differences in precipitation associated with the warmer 500 mb temperatures, 500 mb wind speeds in the range 22-28 mps, and somewhat surprisingly moderate values of 700 mb relative humidity and relatively stable 500 to 700 mb lapse rates. The essential point for the present considerations is that there is a high probability that precipitation is being altered under some weather situations as a result of the ground seeding. This serves as further evidence that ground-

TABLE I. --Estimate of precipitation changes at HAO during seeded period with respect to non-seeded periods. Synoptic parameters are classified according to their relationship to seeding results. Events having wind speeds above 28 mps are eliminated. NP refers to the first nonparametric method, and P the parametric method described by Grant and Mielke (1967). F refers to Equation 1.

Stratification	Number of Events	Method	Precip. Change (Percentage)	Prob. Exceeding
VERY FAVORABLE CONDITIONS				
500 mb Temperature				
(-13C thru -20C)	29 S	NP	over 100	.0485
	35 NS	P	120	.0027
(-21C thru -23C)	26 S	NP	15	.284
	23 NS	P	45	.068
500 mb Wind Speed				
(11 mps thru 21 mps)	56 S	NP	24	.147
	51 NS	P	29	.068
(22 mps thru 28 mps)	28 S	NP	over 100	.0146
	32 NS	P	29	.0465
Parcel Stability				
(+2C thru +3C)	22 S	F	39	
	31 NS			
Lapse Rate Stability				
(-8C thru -16C)	37 S	NP	56	.121
	25 NS	P	56	.0314
Moisture Supply				
(1.6 gm/kgm or more)	30 S	F	67	
	21 NS			
700 mb Relative Humidity				
(50% thru 69%)	41 S	NP	60	.0465
	31 NS	P	30	.062
500 mb Wind Direction				
(northwest)	39 S	NP	25	.154
	53 NS	P	29	.068
FAVORABLE CONDITIONS				
Lapse Rate Stability				
(-17C thru -19C)	47 S	NP	23	.206
	50 NS	P	17	.209

TABLE I. --Continued

Stratification	Number of Events	Method	Precip. Change (Percentage)	Prob. Exceeding
700 mb Relative Humidity				
(70% thru 93%)	28 S	NP	5	.330
	27 NS	P	18	.169
NEUTRAL AND UNFAVORABLE CONDITIONS				
500 mb Temperature				
(-24C thru -27C)	28 S	NP	4	.405
	26 NS	P	1	.476
(-28C thru -35C)	21 S	NP	-12	.242
	25 NS	P	-16	.230
500 mb Wind Speed				
(10 mps or less)	20 S	NP	-19	.187
	26 NS	P	-25	.230
500 mb Wind Direction				
(west)	44 S	NP	5	.397
	34 NS	P	8	.341
(southwest)	21 S	NP	28	.348
	21 NS	P	-8	.397
Moisture Supply				
(1.0 to 1.59 gm/kgm)	29 S	F	-20	
	36 NS			
(less than 1.0 gm/kgm)	23 S	F	-12	
	29 NS			
700 mb Relative Humidity				
(19% thru 49%)	34 S	NP	-33	.164
	51 NS	P	-10	.371
Lapse Rate Stability				
(-20C thru -25C)	20 S	NP	-5	.390
	34 NS	P	8	.382
Parcel Stability				
(-2C thru +1C)	18 S	F	-9	
	19 NS			
(+4C thru +14C)	43 S	F	-6	
	35 NS			

released seeding materials are in fact reaching proper cloud locations a substantial portion of the time.

4. Detection of silver in falling snow

One additional type of evidence is becoming available that suggests that the ground-released seeding materials are distributed through desired target clouds. Silver is being detected in the snowfall in seeded areas in concentrations considerably above natural background levels. Dr. Joe Warburton (1967) has shown this for a number of seeded areas. During the winter of 1966-67 samples of snowfall were collected at Climax directly into large plastic sacks from an elevated site to eliminate any contamination from older drifting snow. These were collected for all days both randomly seeded and for non-seeded days. Dr. Warburton has analyzed these samples for silver. Interpretation of the results is presently in progress. The results are somewhat confusing in that indicated concentrations of silver are higher than expected background levels on both seeded and non-seeded days. Similar samples have been taken for the current season but have not yet been analyzed. For our present considerations, however, let it suffice to say that silver concentration considerably above atmospheric background levels, 3 orders of magnitude in some cases, have been observed.

III. Evidence that seeding materials are not advected to the cloud systems under certain weather conditions

The section above presents a substantial amount of evidence that seeding materials are advected from ground generators to desired locations in some clouds. The evidence is just as clear that ground-released seeding materials are not advected to proper cloud locations under other atmospheric circumstances. The section briefly summarizes evidence to support this latter conclusion.

A. Streamlines and atmospheric stability are not favorable for vertical movement of seeding materials.

The trajectories followed by air parcels over the mountain frequently do not approach near enough to the ground at nearby upwind locations to allow turbulent mixing to be considered as a reasonable basis for the vertical movement of ground-released seeding materials. Actual observational data, however, is limited.

B. Seeding material not present at times at surface ice nuclei counters

Over the eight-year period of the Climax randomized seeding experiment the seeding materials have not been detected at the HAO site in approximately 1/3 of all observations. Figure 1, after Reinking (1968), shows the distributions of cases when seeding materials were detected at HAO after no known seeding within five days prior to the Climax seeding event. In 16% of the cases there were clearly no indications of the seeding materials at HAO. In addition 14% of the cases changes, if any, were negligible and not significant above natural background.

In addition to the approximated 1/3 of the seeding cases when the seeding materials cannot be observed at the HAO site there are times when they are observed at HAO but cannot be detected at the 700 ft higher site at Chalk Mountain. Figure 6 shows the example for the 20-22 December 1967 interval. It can be noted that except for brief intervals the concentrations of ice nuclei at the Chalk Mountain site were a few per liter despite the sharp increases noted at the lower elevation Climax site.

C. Response in the form of increases in ice crystal concentrations is not consistently observed.

Seeding concentrations of ice nuclei are not consistently reflected in snow crystal concentrations. The basic objective of seeding is to increase the concentrations of ice crystals within the cloud system. The successful delivery of seeding materials to the cloud systems should consequently result in increased concentrations of ice crystals. Such increases in snow crystal concentrations in some cases studied have not been observed (Hindman, 1967; Grant, 1968).

D. Kite probes do not consistently confirm the presence of seeding materials in the cloud system.

Seeding materials have not been readily observed with aircraft and kites. Attempts at sampling of seeding materials from within the mountain cloud system have been limited, however. Probing (accumulated probing time less than 2 hours) with aircraft on two separate seeding days failed to detect the seeding materials. Limited samples now available from the kite probe also confirm that there are times when seeding materials are not present in the cloud system, even on occasions when material is observed at mountain top level.

E. Precipitation under some atmospheric conditions is not affected by seeding operations.

No differences in precipitation between randomly seeded and non-seeded events are observed under certain weather situations. This is apparent in Table I. This lack of observable seeding effect could result from the absence of seeding material released from the ground generators and consequently serves as indirect evidence that seeding materials may not be present in the cloud. Other factors could, of course, result in no observable changes in precipitation even with the seeding material present.

IV. Transport mechanisms for ground-released seeding materials in the atmosphere

The determination of dispersion of fine particulate material (e.g. silver iodide) and gaseous material involves two major considerations: (a) source characteristics and (b) atmospheric motions. The source characteristics take into account the strength, height, and dissemination time of the source. These characteristics as well as the source location can be varied substantially in an effort to obtain specific operational objectives.

Atmospheric motions can be separated into two components, turbulence and mean motion. These motions which cannot be controlled or varied at will to meet operational objectives play a leading role in the transport of material. An examination of the turbulent diffusion equation indicates the manner in which these two factors enter into the transport mechanism. For material with negligible fall velocity the time averaged diffusion equation may be written as follows:

$$\frac{\partial \overline{C}}{\partial t} + \overline{U}_j \frac{\partial \overline{C}}{\partial x_j} = k \frac{\partial^2 \overline{C}}{\partial x_j^2} - \frac{\partial \overline{(U'_j C')}}{\partial x_j}$$

Where $\overline{C}$ = mean concentration, $\overline{U}_j$ = j^{th} component of mean velocity, t = time, k = molecular diffusion coefficient, U'_j = fluctuation of velocity from mean value, C' = fluctuation of concentration from mean value, and x_j = j^{th} space coordinate. The various terms may be interpreted as follows:

$$\overline{U}_j \frac{\partial \overline{C}}{\partial x_j} \text{ --- convective transport by mean flow}$$

$$k \frac{\partial^2 \overline{C}}{\partial x_j^2} \text{ --- molecular diffusion}$$

$$-\frac{\partial \overline{U'_j C'}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(K_j \frac{\partial \overline{C}}{\partial x_j} \right) \text{---- turbulent diffusion}$$

Where K_j = coefficient of turbulent diffusion.

In the field molecular diffusion is neglected since the turbulent diffusion is much larger. Turbulence governs the diffusion of airborne material and is a function of atmospheric stability, directional and speed wind shear and surface roughness. The large-scale mean motions govern the direction in which the diffusing cloud of airborne material will be transported. Motions of the convective transport scale are governed by general synoptic flow patterns, mesoscale circulations and the nature of the terrain. In areas of significant topography such as in Colorado transport and turbulence may be influenced by blocking and channeling effects, lee wave phenomena, and slope and valley wind systems. When stable thermal conditions prevail the primary transport mechanism is the convective transport by mean motion in the atmosphere. Past research such as that by Henderson (1965), Langer (1967), Smith (1965) (1963), Willis (1966), Davidson (1961), and Buettner (1964) point out the importance of the above factors on transport and diffusion in mountainous terrain.

The realization of optimal distributions of seeding material in cloud systems presents a complex operational problem. In most, if not all operational programs, the trajectory of released particles has been estimated on a time average basis from the general knowledge of atmospheric motions. Some efforts have been made, primarily on a research basis, to utilize tracers of various sorts to improve the information on the trajectories of seeding particles in real time. This effort by itself, is limited by spatial and temporal capabilities for sampling as well as by the technical problems and accessibility for sampling as well as by the technical problems and accessibility limitation brought about by severe weather under seeding situations.

Ice nuclei measurements, made during the last thirteen years at Chalk Mountain by our Colorado State University group clearly show the wide and rapid fluctuations of seeding materials past the single site. Under certain conditions seeding materials are channeled into the area in concentrations of $\approx 10^6/m^3$ effective at -20° from sites further than eight mile distance. In other flow situations the materials are completely diverted from the area because of topographic influence. Under still other airflow and stability conditions the entire plume is carried completely aloft over the area.

V. Direction for further research

A. Coagulation of seeding materials in the vicinity of the seeding generators

Seeding materials are commonly emitted from the seeding generator at rates of 10^{13} to 10^{14} per sec. Coagulation of these particles in the vicinity of the generator is obviously substantial and varies according to the wind controlled, variable dilution rate in the vicinity of the generators. Coagulation of the seeding particles themselves is probably not of practical significance after the concentration falls below about 10^4/cc. The importance of this coagulation effect in the vicinity of the seeding generators could be of considerable importance in the transport of seeding materials. The problem deserves adequate attention but can probably be reasonably defined with a relatively moderate effort.

B. Laboratory modeling of the transport of seeding materials

The detailed description of the subsequent transport of seeding materials presents a considerably more formidable problem. Tracer studies in the atmosphere can provide increasingly useful information. They are, however, very expensive and are to a large extent limited to non-storm situations and are required for each local area.

The preceding excerpts indicate the complex character of diffusion and transport in mountainous terrain. The need for carefully controlled laboratory modeling efforts to define the wide range of flow characteristics is apparent. A laboratory simulation program in turn needs to be documented by an extensive parallel field measurement program to supply the required input information and for further verification of the modeling parameters.

The basic tool of laboratory simulation is similitude or similarity, defined as a relation between two flow systems (often referred to as model and prototype) such as that proportional alterations of the units of length, mass, and time, measured quantities in the one system go identically (or with a constant multiple of each other) into those in the other. In the case of flow around or over obstacles such as mountains, geometrical, kinematical, dynamical, and thermal similarity must be achieved.

Geometrical similitude exists between model and prototype if the ratios of all corresponding dimensions in model and prototype are equal. This is easily realized by using undistorted scale models of the prototype geometry. Kinematic similitude exists between model and prototype

1. if the paths of homologous (having the same relative position) moving particles are geometrically similar, and
2. if the ratio of the velocities of homologous particles are equal.

Dynamic similitude exists between geometrically and kinematically similar systems if the ratios of all homologous forces in model and prototype are the same. Thermal similarity exists for model and prototype if the density stratification is the same.

If one expresses the steady-state equation of motion in dimensionless form such as

$$\overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = - \left[\frac{g_o L \Delta \overline{T}_o}{\overline{U}_o^2 \overline{T}_o} \right] \frac{\Delta \overline{T}}{\overline{T}_o} g_i + \left(\frac{\nu}{L \overline{U}_o} \right) \frac{\partial^2 \overline{U}_i}{\partial x_j^2} + \left(\frac{K_m}{L \overline{U}_o} \right) \frac{\partial^2 \overline{U}_i}{\partial x_j^2}$$

The necessary similarity criteria appear as coefficients of the dimensionless dependent variables and their derivatives. In this case the pertinent similarity parameters are as follows:

$$(Fr)^2 \quad (\text{Froude number})^2 = \frac{\overline{U_o^2}\, \overline{T}_o}{g_o L \Delta \overline{T}_o}$$

$$(Re) \quad \text{Reynolds number} = \frac{L \overline{U}_o}{\nu}$$

$$(Re_t) \quad \text{Turbulent Reynolds number} = \frac{L \overline{U}_o}{K_m}$$

Therefore, for complete dynamic similarity, the dimensionless parameters Re and Fr would have to be the same for both the model and the prototype (we have neglected the Coriolis acceleration and consequently the Rossby number does not appear). A corresponding analysis of the energy equation reveals that thermal similarity will be attained if the Froude number (inverse of a bulk Richardson number) is equal for model and prototype if the Prandtl numbers are equal. Since air is the fluid in both cases (when a wind tunnel is used for simulation) equality of the Prandtl numbers is assured.

When transport is dominated by convection through the mean motion and the stratification is stable, one may show that the resulting laminar model flow produces a concentration field approximately similar to that for the turbulent prototype. This development, which depends upon comparing the molecular-viscosity-based model Reynolds number with an eddy-viscosity-based prototype Reynolds number, has been prepared for publication in a technical journal and is not reported here.

Essentially this latter development compares the gross mean characteristics of turbulent natural flows over topographical features by a laminar laboratory flow when the scale ratio $L_p/L_m \sim 10^3$. Thus, a tunnel-flow speed is selected so as to equate the Reynolds number $\left(\frac{UL}{\nu}\right)_m$ to the Reynolds number $\left(\frac{UL}{K}\right)_p$.

The preceding discussion introduces the basic problem of thermal similarity; i. e., the matching of the Froude or Richardson numbers for model and prototype. Scorer (1953) and Corby (1954) indicated that thermal similitude requires large temperature gradients ($1° \mathrm{C\ cm}^{-1}$)

at very low flow speeds (9 cm sec^{-1}) for the model and considered such experimental control too difficult to achieve with the conventional wind tunnels. As a result of this problem, most model experiments have been achieved at neutral stability or when the static stability is very small. However, with the recent construction of larger wind tunnels capable of environmental control, the possibility of achieving the required temperature gradients and low flow speeds are an actuality. Recent research in modeling flow over mountains using solid carbon-dioxide to create low flow speeds (~15 cm/sec) and large temperature gradients has also improved the outlook for achieving thermal similarity.

For many cloud seeding operations storm situations may be of primary interest and in such situations it may be possible that prototype neutral stability conditions can be approximated in model experiments. For instance, the type of case in mind is one which the prototype airstream contains 8/8 nimbo-stratus with possible precipitation and having a wet adiabatic lapse rate throughout a great depth.

This type of case may resemble many storm situations in the Chalk Mountain area. Furman (1967) has shown the following characteristics of orographic clouds over Chalk Mountain during the winter season:

Mean cloud depth:	4,000 to 9,000 ft
Cloud bases:	500 to 1,000 ft of the 12,000 ft mountain laboratory
Mean cloud tops:	16,000 ft to 21,000 ft occasional tops reaching 27,000 ft msl.

For such cases the Reynolds number criteria may be relaxed since the flow is geometry dependent for sharp featured topography and essentially independent of Reynolds number.

Not only must the various dimensionless parameters be the same for both model and prototype, but in addition, the boundary conditions must be the same. This latter requirement not only demands geometric similarity of the lower boundary, but also similarity in upstream conditions and in conditions at the upper boundary.

The upstream conditions may be matched rather precisely by setting the model at varying distances from the boundary layer origin in the wind-tunnel test section. The velocity and density distributions that may be obtained in the tunnel are, however, all similar to one another. The upper boundary conditions can only be matched if the study of the prototype is restricted to the lower layers of the atmosphere, approximately one half the height of the troposphere, primarily because the increase in stability $d/dz\ (\ln\rho)$ cannot be reproduced in present wind tunnels without major modifications.

At the present time wind tunnels are capable of simulating certain aspects of atmospheric flow; several restrictions are necessary, however:

1. The prototype region is made comparatively small (~90 mi or less), so the effect of the Coriolis acceleration is negligible (i. e., convective accelerations predominate).
2. The effect of variation of hydrostatic pressure with height is negligible.
3. The effect of compressibility of the air is negligible (where prototype height $L \sim 1$ km or less).
4. The effect of condensation and evaporation processes are neglected (i. e., no clouds or precipitation).
5. The unsteady state of prototype winds are neglected (i. e., the model winds are steady state).

Yet, even with these restrictive assumptions worthwhile results have been obtained from laboratory simulation as briefly summarized in the next paragraph. It must be remembered that much of this work is in a pioneer stage and further research with sophisticated laboratory apparatus may eventually reduce the number of restrictions. However, at the present time, many of the above restrictions are not overly critical for investigations of atmospheric diffusion and particle transport over mountainous terrain in the lower troposphere.

Cermak and staff members of the Fluid Dynamics and Diffusion Laboratory at Colorado State University have undertaken several research projects in laboratory simulation of flow over topographic features. One study which has important implications for this paper was the simulation of airflow over Point Arguello, California (Cermak and Peterka, 1966).

A wind-tunnel study of Point Arguello was motivated by the desire to estimate the diffusion characteristics of toxic gases which might be released in the vicinity of missile launch sites on the U. S. Naval Missile Facility. Accordingly, the primary purpose of this study was to determine if wind patterns observed in a wind tunnel over a 1:12,000 scale model of the Point Arguello area are representative of the prototype wind patterns which are usually stably stratified.

Since inversion flows were of primary interest, the laboratory study was confined primarily to low-speed flow (5 ft/sec) with a maximum attainable temperature difference (wind-tunnel floor was 103° F cooler than the ambient air). Flow patterns for the stable stratification were well documented in the cases of flow approaching from an azimuth of 315° and from 340°.

Two types of flow visualization techniques were used to obtain flow patterns. Photographs of streaks on an indicator paint (white latex paint and congo red) on the model made by releasing ammonia at a variety of points gave an indication of local flow directions at the surface (Figure 7). Photographs of smoke tracers over the model supplemented the chemical indicator method (Figure 8).

Figure 9 shows an example of the flow patterns established with photographs of smoke and indicator paint streaks. The solid portions of the arrows indicate flow in which smoke released near the ground tended to stay close to the surface. The dotted portion of the arrows indicates where the flow--once at the surface--had separated and was somewhat above that surface. In general, the smoke remained attached to the surface until the flow passed over Honda Ridge, separated at the ridge line, and became turbulent downstream from the ridge.

The agreement between model and prototype flow patterns was better than anticipated since the laboratory flow was basically laminar while the field flow was turbulent; however, both were stably stratified to approximately the same degree. Also of interest was the concentration decay rates which were essentially the same. A possible explanation for this agreement may be that in cases where the surface over which the flow occurs is irregular, i. e., composed of hills and valleys, dispersion of a passive additive to the atmosphere may be controlled primarily by

Figure 7. Multiple release ammonia trace data.

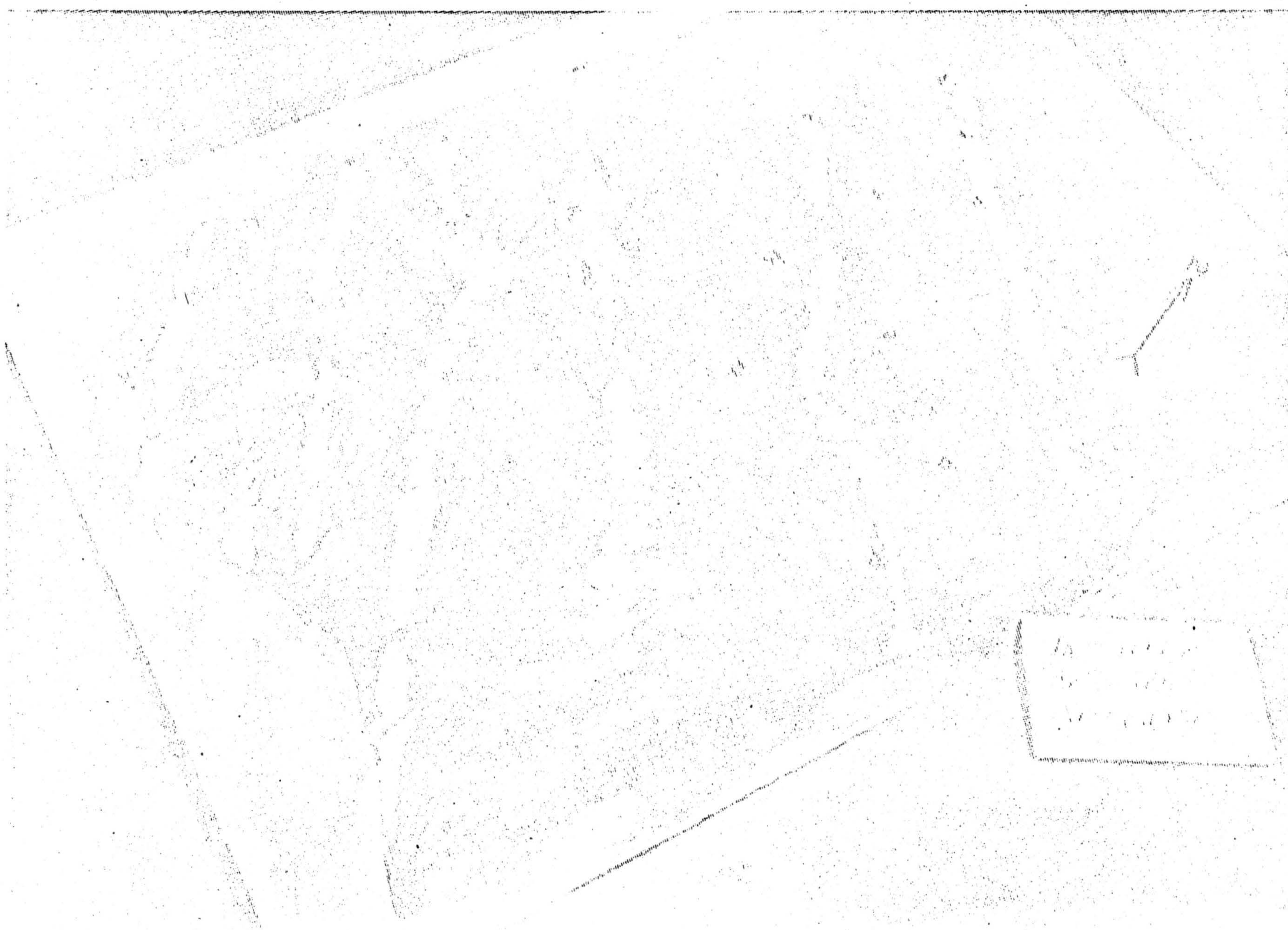

Figure 8. Smoke flow patterns for 340° ambient flow direction.

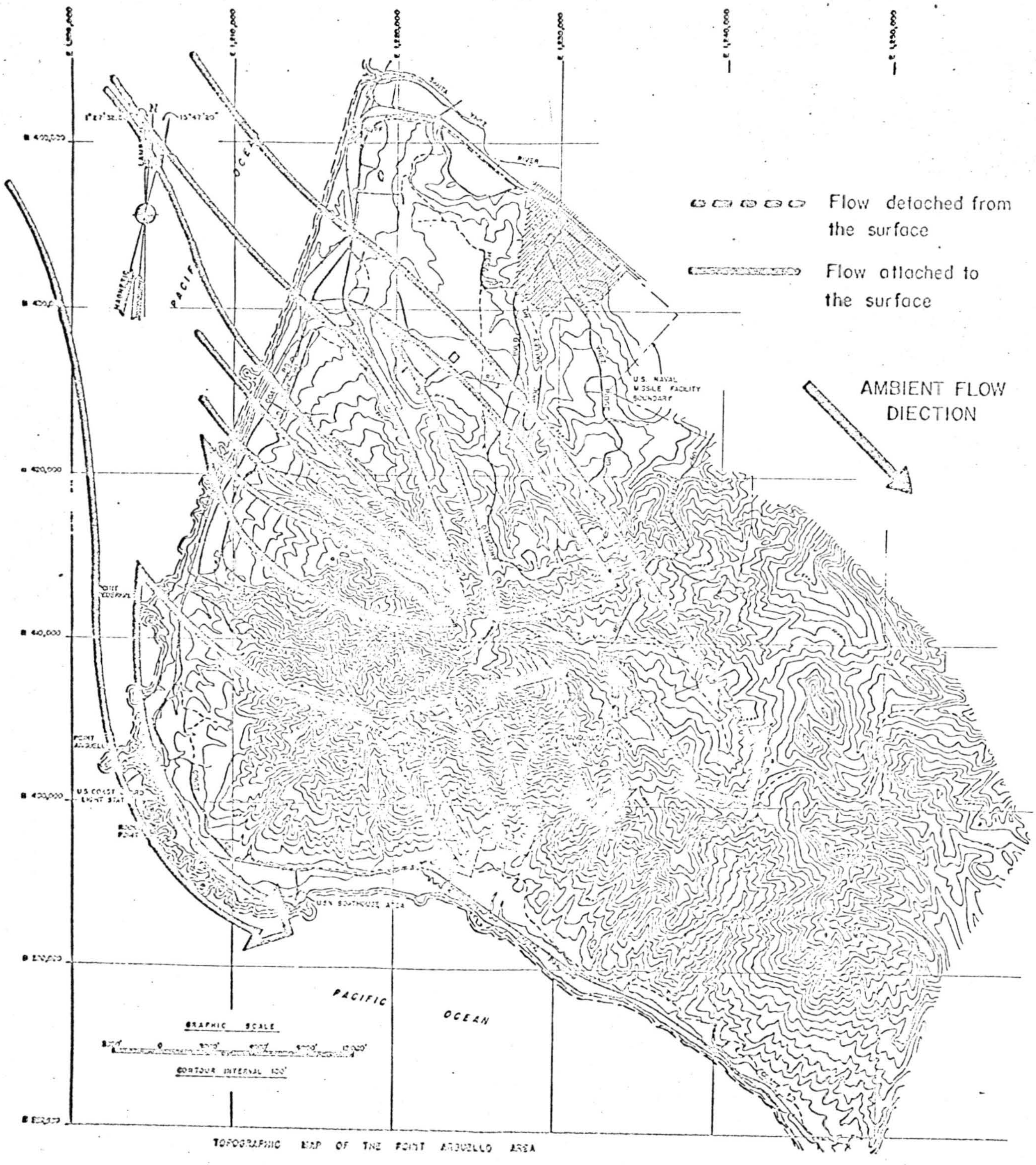

Figure 9. Mean flow patterns for 315° ambient flow directions with inversion conditions.

strong spatial variation in convective transport by the mean motion. Especially in flows with strong stable thermal stratification is this mode of dispersion expected to be dominant.

In general, in comparing the results of the experimental work in the wind tunnel with comparable data from a field study, the authors concluded that excellent similarity existed for wind-flow patterns over the Point Arguello area and the model inversion flow approaching from the northwest.

In conclusion, we can assert that the exploratory efforts made to simulate atmospheric flow over mountainous terrain have produced flow regimes which agree favorably with known prototype data. Particularly in cases where material transport is accomplished chiefly through convection by the mean-motion model derived flow structures have the greatest potential for practical use in planning cloud-seeding operations which utilize ground-based nuclei generators. For these cases, neutral and stably stratified flow over rough terrain, satisfactory simulation is achieved if similar geometry, equal Richardsons numbers and similar upstream flow conditions are attained--Reynolds number equality is not essential. Under these conditions, laboratory model studies can result in the following benefits:

1. The essential variables of topography, wind direction, thermal stratification, and source location can be varied for the study of plume trajectories.

2. The inherent possibility for defining and locating particular problems which might exist on proposed weather sensitive prototype projects.

3. Determination of significant site locations for meteorological instruments and towers, cloud-seeding generators, etc., in the actual prototype for the purpose of obtaining representative observations pertinent to a particular project.

4. A major reduction in time and expense of field studies both by reducing the number required and the amount of data required from those actually initiated.

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