PHYSICAL MECHANISMS OF EXTRA AREA EFFECTS FROM WEATHER MODIFICATION

BY

GERALD J. MULVEY

Atmospheric Science
PAPER NO.
276

US ISSN 0067-0340

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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FROM WEATHER MODIFICATION"

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Gerald J. Mulvey

This report was prepared with support provided by
National Science Foundation Grant ERT 71-01885
Principal Investigator, Lewis O. Grant

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

August 1977

Atmospheric Science Paper No. 276

ABSTRACT OF DISSERTATION

PHYSICAL MECHANISMS OF EXTRA AREA EFFECTS FROM WEATHER MODIFICATIONS

One of the complexities of weather modification, namely extra area effects have long posed an opportunity for the long-term control of the earth's weather. This study investigates the physical mechanisms by which cloud seeding projects may cause extra area effects. The investigations center on one of the simplest of precipitating systems, namely the cold wintertime orographic clouds of the central Rocky Mountains. Three lines of investigation are followed: (1) field studies of seeding material movement in the atmosphere and receiver cloud characteristics, (2) numerical simulation, and (3) historical studies of the affected cloud system.

The field observations consist of case studies of the movement and dispersion of silver iodide from ground based generators. These studies, during the winters of 1974-75 and 1975-76, used nuclei counters aboard two aircraft. Aerosol silver concentration measurements were also made during the last experimental year. The surface observations made as part of the field studies included snow collection for silver analysis, radar observation and ice nuclei measurements.

The aircraft studies established the fact that regions of above backround ice nuclei concentrations extend from the target cloud systems as far as 240 km downwind while exhibiting concentrations from 10 to over 700 ice nuclei per liter active at -20°C. The analysis of silver concentrations in snow confirmed above backround silver concentrations exist in snow samples on days during which cloud seeding occurred in the mountains.

The numerical cloud models were used to investigate the mode of seeding and the seeding requirements of the downwind cloud systems. Case study runs using a cumulus model suggested that seeding the upslope cloud would cause little dynamic intensification. It was therefore inferred that the seeding mode was static. The second cloud model, a rapid glaciation model, estimated the seeding requirements in terms of active ice nuclei or ice crystals for precipitation augmentation to be between 1.0 and 5 $N_o l^{-1}$. An ice crystal transport model was used to predict the survival time for a spectrum of crystal sizes under a variety of conditions. The results indicate that under certain meteorological conditions crystals typically observed in orographic conditions can survive long enough to reach the downwind upslope cloud in concentrations between .5 and 50 $N_o l^{-1}$. The historical studies established characteristics of the typical upslope clouds as well as the surface features controlling their formation. The radar observations showed convective-like echoes migrating within the upslope cloud over the eastern plains of Colorado downwind of Climax. These studies show the existence of at least two feasible mechanisms through which mountain orographic clouds can affect the precipitation on the eastern plains. The studies also outline the meteorological conditions under which the mechanisms investigated are operative.

Gerald John Mulvey
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523
Summer, 1977

ACKNOWLEDGEMENTS

I would like to express my gratitude to my adviser, Professor Lewis O. Grant, for his advice and encouragement during this study. I would also like to thank the other members of my committee: Dr. W. Cotton, Dr. M. Corrin, Dr. P. Mielke, and Dr. S. Karaki. I wish to acknowledge the members of the CSU Cloud Simulation and Aerosol Laboratory: Dr. D. Garvey, Mr. Randy Horn, Mr. C. Swain, Mr. T. Grove, Mr. L. Lilie and Mr. P. Fiegen. I wish to thank the following members of the NCAR Flight Facility: Dr. P. Spyers-Duran and Mr. A. Rodi, and Mr. D. Adams of the CSU Flight Facility. I also wish to thank the following members of the Department of Atmospheric Science, CSU, for their help in various sections of this work: Mr. D. Breed, Mr. D. Blanchar, Mr. J. LeCompte, Ms L. McCall, Ms. G. Meltesen, Mr. V. Scheetz, Ms. J. Davis and Ms. G. Holt. I would like to thank Mr. J. Shaeffer for his work on the snow sample analysis and for his helpful advice and comments all through this research. Thanks are extended to the National Oceanic and Atmospheric Administration for the full cooperation with the radar observations, in particular, to Mr. R. Zabaloni of the Limon site. Thanks also go to Mr. J. Henz for his helpful discussions and cooperation.

In addition, I would like to thank each member of the cooperative snow collection and surface observation network:

Mr. and Mrs. F. Bain
Dr. and Mrs. G. Cobb
Mr. D. Davidson
Mrs. S. Diedrick
Mrs. V. Easem
Mr. R. Everitt
Mr. D. Hanson
Dr. and Mrs. W. Howell
Dr. P. Katen

Mr. M. Pope
Mr. R. Rodriguez
Mr. and Mrs. G. Schnepp
Mr. B. Spence
Mr. J. Unitt
Dr. and Mrs. L. Vardiman
Mr. P. Wetzel
Mr. N. Younger

Last, but not least, I wish to thank my wife, Kathie, for editing this manuscript. Without her constant support and encouragement this work would not have been possible.

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LIST OF SYMBOLS

C	Crystal capacatance factor
C_d	Drag coefficient
D	Crystal diameter
d	Cloud droplet diameter
E_v	Static stability
e	Crystal eccentricity
e_s	Saturation valor pressure with respect to ice
F_m	Ventilation coefficient for mass diffusion
F_q	Ventilation coefficient for heat diffusion
F_v	Average ventilation coefficient
F_α	Kinetic correction factor to the heat diffusion equation
F_β	Kinetic correction factor to the mass diffusion equation
g	Acceleration of gravity
h	Crystal height
H_o	Null hypothesis
K	Thermal conductivity of air
L_s	Latent heat of sublimination
m	Crystal mass
m_v	Molecular weight of water
m_d	Molecular weight of dry air
N	Number of data points in the sample
N_i	Number of ice nuclei active
n_1	Number of data points in sample 1

LIST OF SYMBOLS (cont.)

n_2	Number of data points in sample 2
N_d	Number concentration of droplets of diameter d
p	Environmental pressure
r	Crystal radius
R^*	Universal gas content
$\mathbb{R}_e$	Reynolds number
S	Standard deviations
S_i	Ice saturation ratio
t	Time
T	Temperature
ΔT	Supercooling in degrees below 0°C
u	Updraft speed
V	Crystal fall velocity
Z	Altitude
α	Significance level in the Kolomogrov-Smirnov test
Γ	Environmental lapse rate
Γ_d	Dry adiabatic lapse rate
ρ	Air density

SUBSCRIPTS

s	Sea level
x	At level x
o	Initial

CHAPTER I

INTRODUCTION

Extra-area effects, that is, effects outside the primary target area, from cloud seeding operations offer new possibilities for cloud and mesoscale weather modification. In addition, extra-area effects raise new and more complex social and economic questions. An important step towards the understanding of extra-area effects is the description of the mechanisms whereby they occur. Once this step is complete, predictions of the location, areal extent, and magnitude of the precipitation alteration can be made which will lead to new technological methods for weather modification. Completion of this step will also provide a firm scientific basis upon which social and economic questions can be approached.

1.1 General Objective

The objective of this investigation was to improve our understanding of the physical process which can cause extra-area precipitation alterations. In particular, this work was stimulated by a desire to study the mechanisms related to possible precipitation changes downwind of cold cloud wintertime orographic snow enhancement programs conducted in the Rocky Mountains. The mechanisms investigated in this study may have a more general application to cloud seeding programs.

Two approaches to the problem were used. The first consisted of an extensive field program of observations and measurements during the 1974-75 and 1975-76 winter seasons. These measurements and observations were made both from the surface and in the free atmosphere.

The surface measurements consisted of measurements of the silver concentration in freshly fallen snow and of ice nuclei concentrations. Observations were also made using a surface based weather radar unit. The measurements in the free atmosphere included measurements of ice nuclei concentrations, of aerosol trace metal concentrations, and of cloud structure. The upper level measurements were made from instrumented aircraft. The case studies were augmented by climatological studies of upslope cloud characteristics and by studies of environmental parameters during the period of the Climax I and II experiments 1960-1970 (Grant and Mielke, 1967 and Mielke et al., 1971). The region of investigation extended from the continental divide near Leadville in the central Colorado Rockies eastward into the plains of Colorado.

The second approach used numerical models to examine specific processes which could not be observed in the field program. A set of three numerical models were used to investigate the seeding requirements and the reaction of the upslope clouds to seeding, and to predict the horizontal range of falling ice crystals as they were advected horizontally.

1.2 Specific Objectives

Two specific objectives are formulated for each of the physical and numerical studies and three specific objectives for the historical studies. The objectives for the physical studies are to:

1. Verify the transport of seeding material (silver iodide) from orographic seeding projects into downwind cloud systems;
2. Determine the quantity and spacial distribution of artificially produced active ice nuclei transported to the same systems.

The objectives for the numerical simulation studies are to:

1. Investigate the feasibility of the transport of ice crystals from the orographic clouds over the continental divide near Climax to the cloud systems over the eastern plains of Colorado; and
2. Investigate the effects of the nucleating material transported from the mountain orographic clouds on the downwind cloud systems.

The objectives for the historical studies are to:

1. Identify the cloud systems in the downwind region most likely to be affected by wintertime seeding in the mountains;
2. Describe the physical characteristics of the cloud systems identified; and
3. Estimate the frequency of occurrence of such systems on potential seeding days.

1.3 Review of Extra-Area Studies

Questions on the existence of extra-area effects were first raised by Langmuir (1950). His hypothesis was that periodic seeding (every seven days) conducted in New Mexico was responsible for seven-day periodicities in weather (rainfall, temperature and pressure) across large areas of the continental United States. It was subsequently reported by Holzman (1951), Lewis (1951), Wahl (1951), Hawkins (1952), Brier (1954), and others that such periodicities are evident in data from nonseeded years for the United States as well as in data from other continents. Thus, one could not attribute such periodicities to the effects of weather modification attempts. From that time until the mid-sixties, very little was reported in the literature on any possible extra-area effects. Elliott (1966) first began to investigate possible extra-area effects resulting from the 1957-60 Santa Barbara, California experiments. His hypothesis was that seeding caused (directly or indirectly) an increase in vertical motion field within the cloud which increased the precipitation. His approach was primarily a *post hoc* statistical analysis. The storm systems involved in that experiment were oceanic in nature with a periodic convective band structure enhanced by a coastal orographic uplift. Since then, *post hoc* statistical analyses on several other seeding experiments have been conducted (Williams, 1971; Adderly and Bigg, 1971; Grant, 1971; Mielke, 1971; Janssen *et al.*, 1974; Brier *et al.*, 1974) However, such *post hoc* analyses inherently lack true randomization, thus the results must be considered tentative and can only be used to form limited inferences.

Several physical observations which relate to possible mechanisms have also been reported (Reinking and Grant, 1967; Warburton, 1971; Dumont *et al.*, 1974). To detect above background ice nuclei, Reinking and Grant (1967) used climatological values of ice nuclei concentrations observed at Climax, measurements of ice nuclei at Rabbit Ears Pass, and trajectory analysis. The source of the excess ice nuclei they observed was concluded to be seeding operations more than 400 km upwind in Idaho.

Warburton (1971) analyzed silver concentrations in snow within and up to 240 km downwind of various regions of seeding operations. His conclusions were that there was some evidence indicating a transport of seeding material for a distance of nearly 80 km, but beyond that distance the additional silver from seeding could not be detected above the varying background levels. The analytical technique used was reported to have a detection level of 3×10^{-12} g ml^{-1}.

Dumont (1974) examined satellite photographs of clouds in the Wolf Creek Pass region. From estimates of cloud-top temperature and the physical appearance of the clouds, he estimated that approximately 20% of the cases examined had high cirrus clouds occurring over the lower orographic cloud. These cirrus layers tended to occur more frequently during observations of seeded as opposed to nonseeded events, but the number of days investigated was very small. This would suggest a possible extra-area transport of ice crystals.

Observations made by others not investigating extra-area effects have nonetheless added to the information on the subject. Orgille _et al_. (1971) used a Langer acoustical ice nuclei counter to conduct plume tracking experiments in the Climax region. His primary interest was in the observation of excess ice nuclei plumes from the seeding generators to the cloud base. However, on one occasion he did make several aircraft passes a few kilometers downwind of the trailing edge of a precipitating seeded cloud. He observed high excess ice nuclei concentrations of 10 to 75 number $liter^{-1}$ at several levels (3,350 to 4,270 m msl).

The physical evidence collected by Reinking and Grant (_loc cit_), Warburton (_loc cit_), Dumont (_loc cit_) and Orgille _et al._ (_loc cit_) suggested a transport of seeding material and ice crystals out of the primary target. This material was hypothesized to interact with other cloud systems to affect precipitation. Several reasonable physical mechanisms previously hypothesized to be responsible for extra-area effects were summarized by Brier et al. (1973). These hypotheses can be classified into three general types of possible mechanisms.

Class I is a physical transport of material followed by a micro-physical interaction. This class includes the transport of previously unactivated AgI or unprecipitated ice crystals from the lee side of the cloud edge to another cloud system where "static seeding"[1] occurs. A "static seeding" mode is one where the seeding material acts to increase the cloud efficiency by initiating additional ice crystal growth through enhanced nucleation which consumes the available cloud water. This additional crystal growth does not cause any substantial increase in the vertical velocity field of the treated cloud or in the cloud top height.

The transport of seeding material to the lee side of the mountain ridge where it can begin its long range transport may be accomplished by (1) transit through the cloud; (2) transport in the clear air around or under the cloud; or (3) transport over the ridge during periods when no clouds are present.

Class II is a physical transport followed by a dynamical interaction. Class II has the same particles being transported as in Class I, but the interaction with the second cloud system causes a substantial growth and strengthening of the cloud system. This class contains those mechanisms which involve a physical interaction between the orographic mountain cloud and the downwind cloud. The interaction occurs in such a fashion as to cause an enhancement of the dynamics of the cloud system, called a "dynamic seeding"[2] effect.

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[1]Term used by Simpson and Dennis, 1974, Weather and Climate Modification, ed., W. Hess, Ch. 6, p. 246.

[2]Ibid

The normal concept of "dynamic seeding" is one where the seeding material nucleates ice crystals which grow and in turn release substantial amounts of latent heat. This latent heat release increases the cloud buoyancy and thus increases the vertical velocity and the cloud height.

This class also contains those mechanisms which do not involve a physical interaction such as ice crystals or artificial nuclei interacting with the downwind cloud. Reinking (1968), who showed that ice crystal clouds (contrails) can cause an increase of the horizontal gradient of solar insolation. Such an increase in the gradient of solar insolation could destabilize lower level cloud systems.

The last type, Class III, is a causative dynamical alteration in the atmosphere followed by a mesoscale dynamical alteration at some distance from the primary target area. The mechanisms in this class include those outlined by Elliott (1971). Here the dynamic enhancement of the first cloud system causes an alteration in the atmospheric flow producing a jumpline downstream of the seeding induced "equivalent heat mountain"[3]. The jumpline can also be interpreted as a gravity wave produced by the "equivalent heat mountain" interfacing with the downwind air mass to form a mesoscale convergence line.

It has been suggested by Chappell et al. (1971) that the most probable mode of seeding occurring in the cold orographic clouds over Climax is mircophysical (static). That is, there is no evidence of dynamic intensification of the cloud system occurring when the cloud is seeded. In view of their suggestions, and the physical observations

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[3]Term used by Elliott, 1971, Seminar on Extra-Area Effects of Cloud Seeding, p. 125.

previously mentioned, it appeared that the mechanisms predominating in the case of extra-area effects from Climax should be of Class I or II.

CHAPTER II

GEOGRAPHICAL AREA OF INVESTIGATION

The area under investigation as seen in Figure 2.1 covers the eastern two-thirds of Colorado. It extends from the Climax area on the west (106° 20') to the Kansas-Colorado border and from the northern to the southern Colorado state boundary. The eastern section of this area is part of the Great Plains of the central United States. The elevation of this region gently slopes upward from the Colorado-Kansas border to the foothills of the mountains just west of Denver (105° 30° W). Except for three raised topographic features approximately 300 m above the surrounding terrain the elevation increases uniformly from 1070 to 1830 m. The first of these features is Cheyenne Ridge in northern Colorado and southern Wyoming. The second is the Palmer Lake Divide just south of Denver. The third is Raton Mesa in southern Colorado and northern New Mexico. Between Cheyenne Ridge and the Palmer Lake Divide is the South Platte River which runs northeastward into Nebraska. The Arkansas River lies between the Palmer Lake Divide and Raton Mesa and extends eastward into Kansas and westward into the Climax Region. Along the edge of the plains region is the Front Range. This range is fairly well defined, running from the Palmer Lake Divide northward, with peaks over 4300 m. Southward, the Front Range breaks down into isolated 4300 m peaks and low 2700 m mountains until it joins the Sangre de Cristo Range southwest of Pueblo. West of the Front Range lie three fairly level regions named North Park, Middle Park, and South Park. South Park is to the east of the Climax area. The other two parks are to the north. The Climax region, itself, consists of deep valleys running generally north-south with floors at 300 m and peaks to over 4300 m.

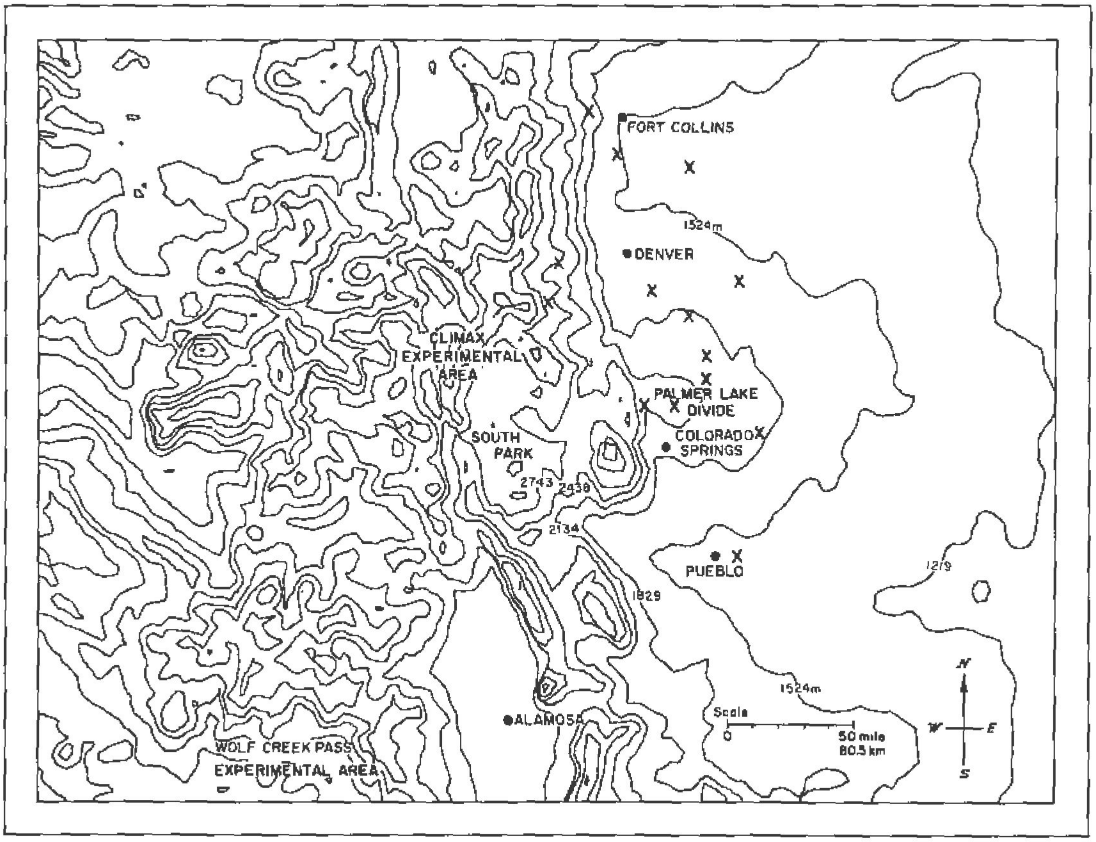

Figure 2.1. Topographic map of Colorado. Elevation contours are every 305m (1000 ft.). Snow sample collection sites are designated by "X".

CHAPTER III

PHYSICAL MECHANISMS

As previously suggested, the most probable classes of mechanisms operating in wintertime orographic seeding programs are of Class I or II. The physical mechanism involves the transport of ice crystals and/or unused AgI nuclei downwind, to interact with cloud systems over the eastern plains region. The development of a framework for testing the hypotheses associated with these classes can be facilitated by dividing the processes involved into the modes of generation, transport and interaction. Within this framework of physical mechanisms, the data requirements necessary to properly test the respective hypotheses can be detailed.

3.1 Modes of Generation of AgI and Transport to the Downwind Cloud Edge

The nucleating agent used in the experiments (AgI) was produced in a propane flame by combustion of the AgI-NaI acetone mixture. The chemical and physical aspects of nuclei generation have been described elsewhere (Fletcher, 1969; Parungo et al., 1974) and will not be repeated here. The physical properties and activity spectrum are presented in Appendix A. The remaining problem is that of the low-level transport and diffusion of the seeding material from the generators to the site of the target cloud. This problem has been investigated for the Climax region by Orgille et al. (1971) and Reid (1976). Orgille used wind tunnel modeling coupled with field measurements, while Reid used field measurements coupled with numerical modeling. These investigations showed that concentrations of active (@ -20°C) ice nuclei in the range of several hundreds to several thousands per liter reach climatological cloud base levels. It was found that the spacial variation in ice nuclei concentrations are influenced greatly by air flow channeling, topographic features, mountain-valley breezes, nocturnal inversions, synoptic scale wind velocity, and free environment stability. The field observations indicate that nocturnal down-valley winds can carry the generator effluent tens of kilometers upwind of the generator, thus presenting, for transport to the target cloud, a potentially large source area of artificial ice nuclei.

The transport of the seeding material to the lee side of the mountain ridge can be accomplished in two possible modes. These were discussed in Section 1.3 as Class I, modes 1, 2, and 3 of the general types of mechanisms in the Review of Extra-Area Studies. Of these modes, only during transport through the cloud, (Class I, 1) would substantial losses of material occur. These losses would be due to nucleation and scavenging.

Observations of Orgille obtained from the Queen Air aircraft under precipitating conditions indicated that ice nuclei in concentrations on the order of 10 to 100 No ℓ^{-1} reach the lee slope region. The observations suggest that for his specific cases between 90 and 95% of the active ice nuclei entering the cloud base was removed.

3.2 Mode of Generation of Ice Crystals

When cold orographic clouds are seeded with AgI, the hypothesis is that the AgI particles will act as active ice nuclei in the naturally nuclei-deficient clouds; the ice crystals thus formed will grow and fall out, and precipitation will be increased. This has been verified to be correct by Chappell (1970), Grant and Elliot (1974) and others. Surface observations of ice crystals from seeded and unseeded Colorado orographic systems have been made by Vardiman and Hartzell (1976), Vardiman et al. (1974), Chappell (1970), Grant (1968), Hindiman (1967), and Grant (1965).

These authors have established typical sizes for ice crystals precipitating from non-seeded clouds and also the ice crystal size spectra from seeded and nonseeded cloud systems. Vardiman and Hartzell (loc. cit) acquired and analyzed almost continuous ice crystal data from a series of 66 cases, 39 seeded and 27 nonseeded of winter orographic storms. From a statistical analysis of the data, they concluded that, there was a significant increase (335%) in the concentration of ice crystals and a decrease (26%) in the degree of crystal riming from seeded as opposed to nonseeded storms. These observations are consistent with the general hypothesis outlined above for seeding cold orographic clouds. In addition, they reported a significant increase (21%) in the crystal diameter. This can be explained if it is assumed that complete glaciation of the cloud does not occur, that is, the cloud is still supersaturated with respect to ice during a seeded event and the seeding starts crystal growth closer to the upwind cloud edge. This would place larger numbers of ice crystals at cloud top where they would have long trajectories to the surface. If the premise of a supersaturated cloud is accepted, these ice crystals would continue to grow throughout their trajectory. This process would differ from the natural case in the number of ice nuclei activated per time interval in the high levels in the cloud.

A continual supply of new ice crystals would be provided as the air parcels ascend to colder layers and spend more time within the cloud. Because of this, one could reasonably suggest that the ice crystals exiting the downwind cloud edge should have characteristics similar to the crystals observed at the surface near the ridge top. The net results of the process would be both a higher concentration of ice crystals and larger ice crystals exiting the downwind edge of the cloud during seeded as opposed to nonseeded events. The increase in size may occur even in the colder cloud cases, at the expense of cloud droplet and crystal riming growth. The increase in concentration and size could bring these parameters above the critical levels where the crystals would survive the transport downwind and in sufficient concentrations to enhance the precipitation efficiency of the downwind clouds.

3.3 Mode of Transport

Once the artificial nuclei and/or ice crystals leave the target cloud region they are subjected to a downward vertical motion in the mountain lee region. This could be followed by an upward, vertical motion to compensate for overshoot of the equilibrium level and result in possible wave motion, depending on the wind velocity and environmental stability. The mixture composed of ice crystals and AgI particles will then be advected downwind while turbulent dispersion, sedimentation, and, for ice crystals, mass changes occur. The effect of any lee wave system on the survival times of ice crystals undergoing a transport would depend on the physical dimensions of any ice saturated (or supersaturated) and subsaturated regions. That fraction of the mixture which survives the transit and arrives over the downwind cloud system could then interact with downwind cloud systems. This interaction could occur either directly by incorporation into the low level cloud, or indirectly by glaciating upper level clouds. The incorporation of the transported particles into the upper level clouds could stimulate the precipitation processes. The precipitable particles from this cloud would then settle into the lower level cloud and thus effectively seed them. Such a system is what Jiusto and Weickmann (1973) called a seeder-spender cloud configuration. The increase in the concentrations of active ice nuclei and ice crystals can also act to increase the efficiency of an already existing "seeder-spender" cloud system.

3.4 Mode of Interaction

Artificial ice nuclei and/or ice crystals which form in the orographic clouds over the Continental Divide, can alter the precipitation received downwind at the surface in several ways. The nuclei and/or ice crystals can enter an upper level cloud layer and stimulate precipitation in this system by nucleating additional ice crystals which can grow, or allowing the transported ice crystals to grow. In both cases, the ice crystals could fall into a lower cloud system. Once in this lower cloud system the crystals could grow by vapor deposition, by riming and/or by aggregation. This would increase the precipitation efficiency of the cloud layer. The injection of the ice crystals from the "seeder" cloud could also trigger a dynamic enhancement (dynamic seeding) of the lower cloud system. This dynamic enhancement would result in an increased growth of the more convective regions of the cloud due to the release of latent heat. The cloud top rise would nucleate additional ice crystals following the "dynamic seeding" hypothesis of Simpson et al. (1965). It was hypothesized that the enhancement of the vertical velocity field, would result in an elevated cloud top and an increase in the sub cloud moisture flux. Thus by a combination of entrained ice crystals from upper level clouds, additional ice crystals nucleated due to the cloud top rise, and an increased moisture flux, it is hypothesized that the precipitation received at the surface would be altered.

The above mechanisms require an upper level cloud layer to be present, but such layers are not always present. Lacking such layers the ice crystals or the ice nuclei remaining after the crystals completely sublimed and artificial nuclei could form a thin cloud layer in a supersaturated (with respect to ice) layer. Bigg and Meade (1971) did create thin clouds by seeding such a layer with silver iodide. But it is unlikely that such clouds would cause radiational gradients (such as those proposed by Reinking for contrails) over large areas of the upslope cloud because of the low level of such a cloud and the losses due to fallout. A "seeder-spender" system could be established if the supersaturated layer was very near the top of the lower level cloud and the ice crystals and ice nuclei were not reaching the lower level cloud.

An alternate hypothesis involving dynamic modification of wintertime cloud systems in which augmented ice crystal clouds may enhance surface temperature gradients has been suggested. In this hypothesis the boundary layer immediately downwind of the seeded orographic cloud may be modified by ice crystal-cloud-induced radiational gradients which in turn cause a dynamic alteration in the flow. This could effect lee wave or other gravational wave development and propagation which could inturn affect the ice crystal survival times or effect the downwind cloud directly. The possibility of such alterations were not investigated here.

This brings us to a direct injection mechanism where the ice crystals and/or silver iodide enter the low level cloud directly. Depending on where the mixture entered the cloud, the mode of interaction could be "static" or "dynamic". The static mode includes the possibility that convective regions could be glaciated and spread the ice crystals to adjacent regions of the cloud where additional growth and precipitation enhancement could occur. The direct injection mode could be further enhanced by transport of the ice crystal-silver iodide mixture to lower levels of the cloud through entrainment into the convective regions and transport in downdrafts. The advantage here could be that the residence time in the cloud would be increased, thus increasing the final mass of the crystals precipitating out of the cloud base.

The data necessary for testing the hypothesis or hypotheses is treated in separate sections under the modes of generation transport, and interaction.

Investigations into the mode of generation were conducted prior to or parallel to this study. The investigations of Parungo et al. (loc. cit.), Gerber et al. (1972), Gerber et al. (1970), Orgille et al. (loc. cit.), and Reid (loc. cit.) concerned the mode of generation, the physical properties, and the transport to the target cloud of the silver iodide aerosol. The investigation of Vardiman et al. (1974), Vardiman and Hartzel (1976) and Chappell (1970) concerned the generation and the physical properties of the ice crystal phase. Together these two groups of investigators have sufficiently described the mode of generation for both ice crystals and silver iodide.

The mode of transport, however, has not received detailed scrutiny. Investigators of seeding plume movement almost always cease observations at the downwind edge of the cloud, and, to the author's knowledge, there has been no systematic investigation of the long-distance downwin transport of ice crystals from seeded and non-seeded orographic clouds. To start the investigation of the mode of transport it was necessary to determine if seeding material was leaving the target area under a variety of conditions. If it was, it would be necessary to estimate the amount of material undergoing the transport. For ice crystals, such measurements were not possible; therefore, it was necessary to establish a climatology of conditions, including the availability of the two cloud systems under which a long range transport could occur. In addition, it was necessary to determine if any transport mechanism was available to couple the high altitude transported material with low level cloud systems. Further, it was necessary to develop a numerical model capable of simulating the mass changes of a falling crystal and thus predict the maximum horizontal range of an optimum ice crystal size.

Because of the difficulties and uncertainties associated with the collection of data needed to identify the mode of interaction, a decision was made to use detailed cloud microphysical numerical models to help identify the mode of interaction. It remained to identify the types of cloud systems of most interest, the microphysical and rough dynamical properties of such a system, and to choose appropriate models. The model could then be used to simulate the response of the clouds of interest to seeding. The input parameter information was collected through historical studies and through observations made during the physical studies.

CHAPTER IV

EXPERIMENTAL EVIDENCE

Investigations into the mode of transport of silver iodide particle were conducted through an extensive program of physical studies. They consisted of a field observation program conducted for two winter seasons, 1974-75 (Downwind Seed I) and 1975-76 (Downwind Seed II). The purpose of these observations was to collect data to determine if seeding material was leaving the Climax area, undergoing long range transpor and interacting with clouds forming over the eastern plains and foothill region of eastern Colorado. The field program consisted of two parts, aircraft observations and surface observations.

The aircraft observations were taken on days when the seeding generators were and were not operating, both within and downwind of the Climax target site. On seeded days allowances were made for the time delay in the transport of the seeding material. The observations were made by two aircraft operating at approximately the same time. The aircraft flew predetermined flight tracks at specific altitudes. The first aircraft was the NCAR Queen Air with a Langer type acoustical ice nuclei counter aboard as well as state parameter measurement, environmental winds, and position determination systems. The Queen Air utiliz Rosemount compensated pressure transducers for pressure altitude, stati pressure and true airspeed; Rosemount platinum resistance thermometer and a reverse flow thermometer for environmental temperature; EG&G Thermoelectric Dew Point Hygrometer for environmental moisture content, and an inertial navigation system for position and environmental wind estimates. It also carried a time lapse camera.

The acoustical ice nuclei counter is a continuous flow counter with a flowrate of approximately 10 ℓ min^{-1}. The details of the acoustical counter's construction and operation have been given elsewhere (Langer et al., 1967; Langer, 1973) and are summarized in Appendix B.

The second aircraft was the CSU Aerocommander 500-B equipped with a modified Mee optical ice nucleus counter, the CSU Inline Aerosol Sampling System (IASS); state parameter measurement instruments and VOR-DME position determination systems. The Mee ice nuclei counter is a continuous flow system with a flowrate of 10 ℓ min^{-1}. The construction details of the counter and description of operation have been given elsewhere (Mee, 1972; modifications, Garvey, 1976) and are summarized in Appendix B.

The IASS is a small aerosol collection system for VFR conditions that is outside of clouds. It was operated in a check-out mode during the last few days of Downwind Seed I and in a data collection mode during Downwind Seed II.

The system consists of a vertical array of four stainless steel intake nozzles extending from a streamlined air foil where the collection mediums are located. The lowest intake nozzle is 18 cm above the aircraft skin (12 cm above the airframe boundary layer top). The collection mediums are membrane filters and graphite atomic absorption furnace cups, which could be analyzed for active ice nuclei concentrations and trace metal mass, respectively. The flowrates through the intake nozzles were regulated by hand at approximately 2 ℓ min^{-1}. Sampling usually proceeded for 20-30 minutes. The system design and sampling errors have been described elsewhere (Mulvey and Sheaffer, 1976). The location of the IASS and Mee counter sample intakes on the 500-B are shown in figure 4.1.

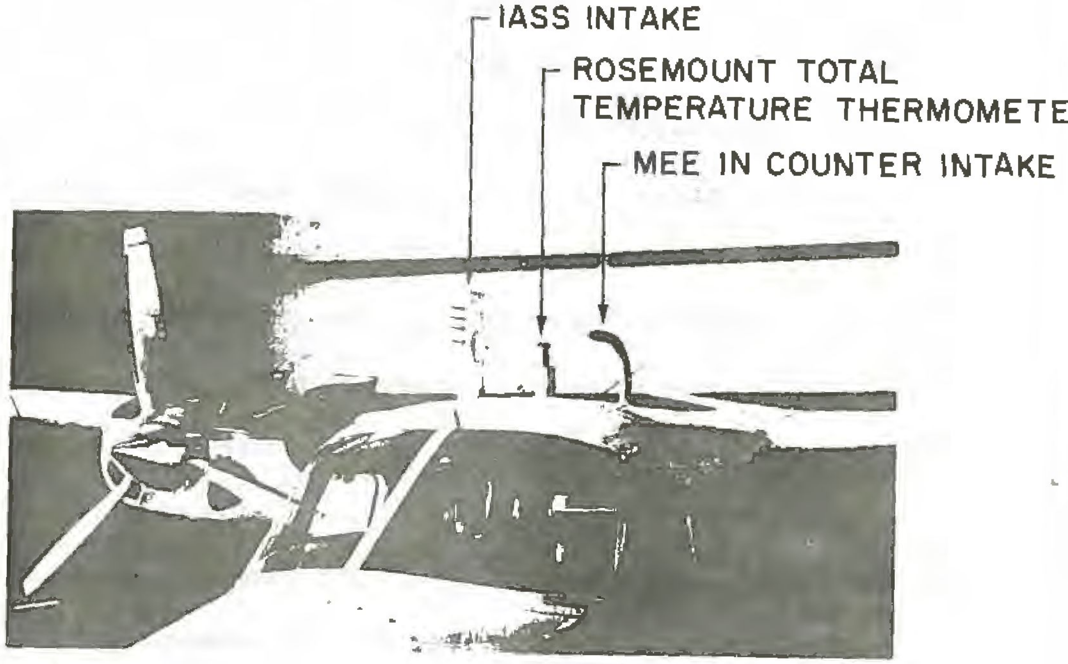

Figure 4.1. Aero Commander sampling system intakes.

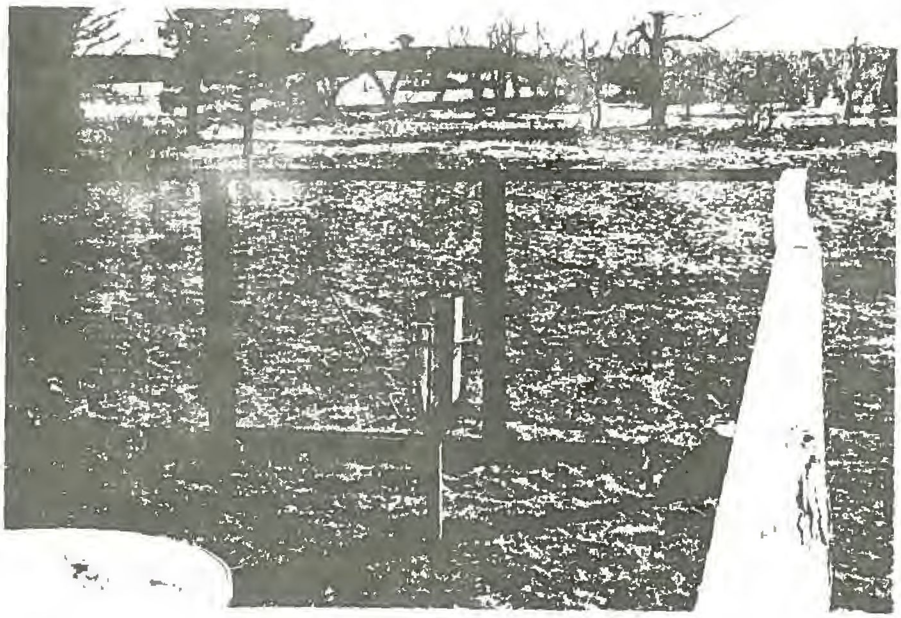

Figure 4.2. Typical snow sampling collection station (Cherry Creek Dam).

parameter measurement systems consisted of a NASA calibrated boom and Rosemount compensated pressure transducers for pressure altitude, static pressure and true airspeed, Rosemount platinum resistance thermometer for temperature, and a Cambridge thermoelectric hygrometer for humidity. A comparison of aircraft characteristic and instrumentation specification is provided in Table 4-1. The data from both aircrafts were recorded at one-second intervals, after preliminary signal processing, on magnetic tape for later computer analysis.

The Langer acoustical counter, and Mee optical counter were compared at the beginning of Downwind Seed II using an artificial test ice nucleant. The results of the comparison tests indicate a general agreement in the temperature and concentration ranges of interest between the instruments involved (Garvey, 1976). A graphical presentation of the test results are shown in Appendix B. No effort was made to make the intake probes for these instruments isokinetic, isoaxial, or to reduce internal deposition. The data from these instruments must therefore be regarded as qualitative and represent conservative values.

The supporting meteorological observations consisted of freshly fallen snow sample collections, special surface radar observations, limited surface ice nuclei concentration measurements, special radiosonde ascents from Chalk Mountain and surface weather observations from the National Weather Service network.

The freshly fallen snow samples were collected on the eastern plains and near foothill regions (see Figure 2.1). The procedure which was followed by observers in collecting the samples was to expose a clean plastic bag whenever it was forecast to snow or was snowing at their site. After it had stopped snowing, the bags were sealed, marked

TABLE 4.1

AIRCRAFT INSTRUMENTATION CHARACTERISTICS

QUEEN AIR (Burris et al. 1973)

Parameter	Instrument Type	Range	Accuracy	Response
stagnation air temperature	Platinum Resistance total temp. probe	-70 to +30° C	± 0.2° C	1.0 sec
	Platinum Resistance reverse flow probe	-60 to +40° C	± 0.5° C	8-10 sec
moisture content	Thermoelectric dewpoint hygrometer	-50 to +50° C	± 0.5° C above 0° C ± 1.0° C below 0° C	3° C/sec
airspeed and pressure altitude	Variable capacatance pressure transducer	300 to 1035 mb	± 1.0 mb	0.025 sec

AERO COMMANDER 500-B

Parameter	Instrument Type	Range	Accuracy	Response
stagnation air temperature	Platinum Resistance total temp. probe	-70 to +30° C	± 0.2° C	1.0 sec
moisture content	Thermoelectric dewpoint hygrometer	-50 to +50° C	± 0.5°C above 0° C, ± 1.0° C below 0° C	3° C/sec
airspeed and pressure altitude	Variable capacatance pressure transducer	300 to 1035 mb	± 1.0 mb	0.025 sec

and stored in their home freezers. The cooperative observers were not told if seeding was occurring at Climax. The bags were supported approximately one meter above the surface in specially constructed metal frames as shown in Fig. 4.2. The elevations of the collection stations ranged from 2377 m msl in the foothills to 1676 m msl on the plains. The collection period varied depending on the duration of the snowfall at the individual site and on the schedule of the individual observers.

The snow samples were analyzed for trace silver using a flameless atomic absorption technique. The details of the collection and analysis techniques are given elsewhere (Mulvey and Grant, 1976).

The limited ice nucleus concentration measurements and observations of cloud cover wind direction and temperature were taken during the 1974-75 winter season at the High Altitude Observatory near Climax and at the Greenland 7NE, using a Bigg-Warner type of over-pressure expansion chamber. Greenland 7NE is the ranch of Mr. F. Bains, who operates a Coloardo State cooperative precipitation station on the Palmer Lake Divide. Observations were made at -20°C every hour with a spectrum taken at 2°C intervals from -10°C to -30°C every three hours.

The special radiosonde ascents from the top of Chalk Mountain (near Climax, Co.) were make twice daily during experimental periods. The first ascent was near 1030 MST and the second near 1500 MST. Ascents could not be made during the early morning or evening due to the inaccessibility of the launch site.

The special radar observations consisted of additional contouring of radar returns every 6dBz from MDS (-109 dBM) during selected storm situations. The radar unit was the WSR-57 10 cm. unit located at Limon, Colorado, on the Palmer Lake Divide. For details of the radar unit see

see Appendix C. Observations of ice crystals involved in a long range transport were not made during either winter season.

4.1 Aircraft Observations

The aircraft flight patterns chosen for these observations (see figure 4.3) were designed to supply information on the background ice nuclei levels and on the transport of seeding material as detected by above background ice nuclei levels as well as aerosol silver concentrations over specific regions downwind of the primary Climax target region. The altitudes and other specifics of the flights are given in Table 4.2. It was decided that these flight levels and patterns would allow a determination of accurate background levels; specifically, the level and transport of inadvertent anthropogenic ice nuclei. The levels were also chosen to measure the plumes of seeding material within the instrumentation limits and the Federal Aviation Regulations. Flights were conducted on seeded days when clouds were and were not present over the target site. An outline of the experimental periods and aircraft flights is given in Table 4.3. A total of 12 flights were made by the NCAR Queen Air during seven experimental periods. Of these, three were seeded periods and four were background (nonseeded) periods. Several of the flights produced limited data or were cut short due to aircraft or instrumentation systems failure (two seeded, one nonseeded). The CSU Aerocommander flew 15 flights 11 seeded, four nonseeded, during seven experimental periods. Two flights on seeded days produced limited data. During Downwind Seed I, to compensate for limited Queen Air availability, the CSU Aerocommander on occasion expanded its flight tracks to include South Park.

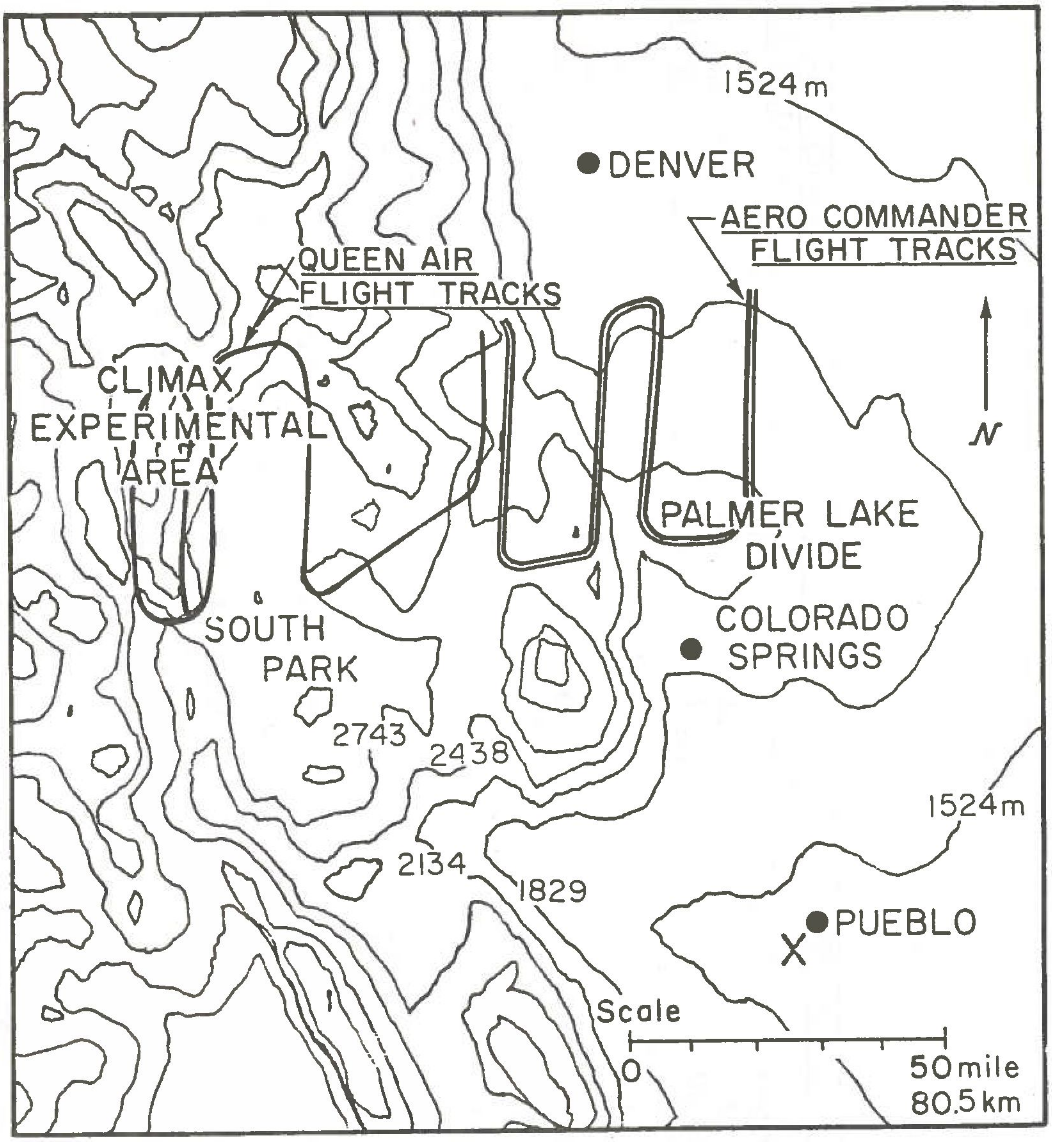

Figure 4.3. Aircraft Flight Tracks over Eastern Colorado. Elevation Contours are shown for 305 m (1000 ft.) intervals.

TABLE 4.3

AIRCRAFT INVESTIGATION SUMMARY

DATE OF EXPERIMENTAL PERIOD	WAS PERIOD SEEDED	QUEEN AIR			AERO COMMANDER 500-B			
			TYPE OF DATA AVAILABLE			TYPE OF DATA AVAILABLE		
		NUMBER OF FLIGHTS	ICE NUCLEI CONC.	STATE PARAMETER	NUMBER OF FLIGHTS	ICE NUCLEI CONC.	STATE PARAMETER	TRACE METAL
12/20-21/74	Yes	0			3	Yes	Yes	No
1/3-4/75	Yes	2	No	Yes †	2	Yes	Yes	No
1/8/75	No	1	Yes	Yes	1	Yes	Yes	No
1/10/75	Yes	1	Yes	Yes	2	No	Yes	No
1/16-17/75	Yes	3	Yes	Yes	2	Yes	Yes	No
12/10/75	No	1	Yes	Yes	0			
12/13/75	No	1	Yes	Yes	0			
1/27-28/76	No	3	Yes	Yes	4	Yes	Yes	Yes
2/5/76	Yes	0			2	Yes	Yes	Yes

†Flight cut short due to aircraft malfunction.

TABLE 4.2 AIRCRAFT AREA ASSIGNMENT AND FLIGHT LEVEL SUMMARY

SEASON	AIRCRAFT	USUAL AREA OF FLIGHT TRACKS	NOMINAL FLIGHT LEVELS*
Downwind Seed I Winter Season 1974-1975	Queen Air	South Park North of Buena Vista between 105.4° and 106.0°W Longitude	4115 3510
	Aero Commander	Palmer Lake Divide South of Denver between 104.4° and 105.3°W Longitude	4575 3050 m
Downwind Seed II Winter Season 1975-1976	Queen Air	South Park North of Buena Vista between 105.4° and 106.2°W Longitude	4570 3775
	Aero Commander	Palmer Lake Divide South of Denver between 104.4° and 105.3°W Longitude	4270 m 3810 m

*Changes in Flight Levels were made in flight to conform to FAA regulations and for cloud penetrations.

During the two winter seasons the Langer counter randomly recorded anomalous ice nuclei concentration spikes during seeded and nonseeded events. This behavior was also observed by Reid (1976).

A new electronic processor used during Downwind Seed II showed these spikes to be a characteristic of the old system and not related to the nuclei concentrations, therefore, the spikes were ignored in all analyses.

The flights on seeded days were schedules so as to allow at least two hours to elapse between the start of the generators and the commencement of measurements. On one occasion, 16 January 1975, the morning flight was started before the seeding generators were started due to generator malfunction.

4.1.1 Aircraft-Measured Background Levels of Ice Nuclei and Silver

Background (nonseeded) measurements of ice nuclei concentrations and aerosol silver concentrations were necessary to establish baseline values upon which the observations of seeded days could be evaluated. This was needed because of spacial variations in the sources of ice nuclei and silver, which are reflected in the concentrations in air. Background flights were conducted on 10 December 1975, 13 December 1975 and 8 January 1975, and 27 and 28 January 1976. These flights were made over the same tracks as were flights conducted during a seeding event. The flights of 8 January 1975 and 27 and 28 January 1976 included both aircrafts, while that of 10 and 13 December 1975 included only the Queen Air.

The background ice nuclei levels, measured over South Park by the Langer counter, were generally in the 0.5 to 1.0 number per liter (No.

ℓ^{-1})* (at -20°) range at all flight levels. This is in agreement with climatological records of ice nuclei concentration measurements taken at Climax. The Mee counter flown over southern Denver and the Palmer Lake Divide measured background levels between .1 and 5 No. ℓ^{-1} at levels about 3050 m msl. In light of the method of adjusting the ice nucleus concentration to a comparable temperature (-20°C) and the possible influence of inadvertent anthropogenic ice nuclei from Denver and Colorado Springs, these levels also compare well with the Climax records.

The flight of 13 December 1975 was conducted during the late morning hours. (On the days surrounding the aircraft flight upslope clouds were present over the eastern plains of Colorado.) On the day in question, the upper level winds (500 mb) were from the southwest. The main surface feature was a cold intrusion of air associated with a high pressure system to the north of Colorado. The flight tracks were mainly over the South Park region where clouds were in evidence. Penetrations of these clouds were made. The morning Denver radiosonde showed a low level inversion at about 1700 m msl. Above the inversion a conditionally unstable layer was present up to 3000 m. The atmosphere was observed to be stable throughout the rest of the sounding. The evening Denver radiosonde showed a stable upslope cloud with a top of 2700 m. In the uppermost cloud layer was the top of a 3.5°C temperature inversion. The air above cloud top had some slight conditional instability. The low level airflow measured by the Queen Air upon ascent north and west of Jefferson County Airport (JEFCO) was mainly from the east to the south. This easterly flow was confirmed by surface observations at Denver, Colorado

*Note: All ice nuclei concentrations described in this paper are those active at -20°C and have the units of Number per liter (No. ℓ^{-1}) unless otherwise stated.

Springs, and Pueblo for the period of aircraft observations. The highly sheared layer, where easterly low level flow made the transition to upper level westerly flow, was quite thin. It occurred at about the 2440 m (msl) level. The flight track showed progressively lower IN concentrations with increasing altitude. The one section of flight track which showed above-background levels (10-30 No. ℓ^{-1}) occurs just east of the Front Range. This attributed to inadvertent anthropogenic sources in the foothill cities, based on surface winds, and topographic uplift. Most of the Queen Air measurements were made over South Park. In the region the background concentration averaged between 0.5-4.0 No. ℓ^{-1}.

The flights on 8 January 1975 were conducted during late morning to mid-afternoon, thus insuring a well-mixed environment so that local IN as well as general background would be measured. A collapsing weak high pressure system over the western slopes with a stationary frontal system located in central Utah characterized this day. High clouds (ceiling 6100 m. to unlimited) covered the skies over the area of interest. The Denver radiosonde revealed a weak 0.4°C inversion 10 mb. thick at 560 mb. (12Z, 8 January 1975). By the evening sounding (00Z, 9 January) the inversion had degraded to a stable layer.

The results of the Queen Air measurements are shown in figure 4.4. The measurements at the two levels sampled (3,660 and 4,145 m. msl.), average between 0.5 to 1.0 No. ℓ^{-1}. The measurements were made with W to WSW winds and did not show any discernable influence of anthropogenic IN from Leadville. The Aerocommander 500-B measurements made south of Denver show considerable evidence of inadvertant anthropogenic ice nuclei at 2440 m. msl with concentrations ranging from 3.0-45.0 No. ℓ^{-1} and an average concentration of 19.0 No. ℓ^{-1}. At 3050 m. concentrations of ice

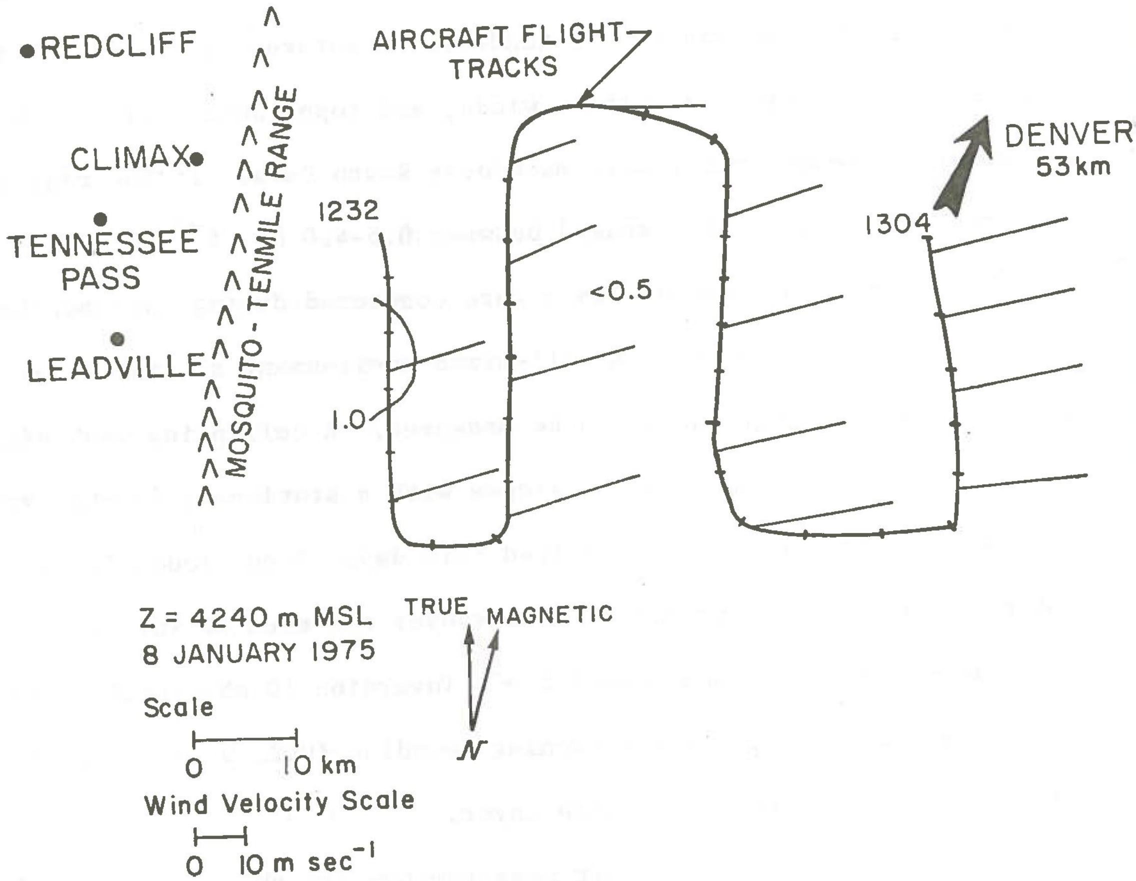

Figure 4.4. Queen Air flight tracks, ice nuclei concentrations (at −20°C) and the aircraft measured windfield.

nuclei south of the city range from less than 0.1 to 64.0 No. ℓ^{-1}, with the average being 8.6 No. ℓ^{-1}. Background levels of less than 0.1 to 3.0 seem to extend over a large section of the flight track, mostly in the southern portions. Concentrations at still higher levels (4270 m) show other unusual patterns. Low concentration exists over the northern part of the track less than 0.1-4.0 while an isolated band of 10-15 No. ℓ^{-1} was measured in the southern half. The average over the track was 4.9, if one localized region of extremely high counts is neglected. There was a tendency for the concentration to drop off at the extreme southern and western sections of the tracks. The decrease of active ice nuclei concentrations with increasing altitude suggests a surface source possibly inadvertent anthropogenetic. The other background flights made by the Queen Air show results similar to those of the 8 January flight. Generally concentrations over South Park averaged from 0.5 to 1.0 No. ℓ^{-1} with no clear geographic distribution or pattern.

A series of aircraft flights were conducted between Fort Collins and Castle Rock, Colorado on six days during 1972 under another research project (Edwards, 1973). The ice nuclei concentrations measured with the Langer acoustical counter averaged between 0.1 and 1.0 No. ℓ^{-1}. These observations showed a general decrease in the ice nuclei concentrations with increasing height. Two additional flights were made over Denver and one over Pueblo. In all cases the ice nuclei concentrations were higher over the cities. A composite of the ice nuclei concentration measurements from flights on six days during 1972 showed an average decrease (by a factor of 50) in concentration with increasing altitude over Denver. Surface observations of ice nuclei were also made in the Denver region by VanValin and Pueschell (1976). The conclusion of their study was that human activity in Denver is a low-grade source of ice nuclei.

The background silver concentration measurements were made on 27 January 1976 and 28 January 1976. The results are summarized in Table 4.4. During these flights the upper level flow (500 mb) was from the northwest. At the surface a collapsing high pressure system was situated over the western half of Colorado. Some clouds were visible over the mountains to the west of the Aerocommander flight tracks. Cirrus and wave clouds were visible far above the highest aircraft flight level (4300 m). Thin mid-level clouds at the sampling level were present during the flight of 27 January. Both Denver radiosondes taken on 27 January showed an inversion layer near 4000 m. capped by stable layers over 2000 m. thick. The morning sounding on 28 January showed an inversion near 5000 m. The evening sounding placed the inversion at 4000 m. For both soundings, the inversions were capped by stable layers over 2000 m thick. These flights showed that the background levels of silver were generally below 0.1 ng m^{-3}. Higher background levels (1.0 ng m^{-3}) were measured on occasion at 3810 m. msl. This high silver concentration is believed to be inadvertent anthropogenic silver from Denver and/or Colorado Springs.

Background concentrations of aerosol silver generally vary with the sampler location (urban, suburban, or rural) and the prevailing meteorological conditions. The results from surface aerosol samples collected before, during, and after a high pollution period in Ghent, Belgium were reported by Demuynck et al. (1976). These samples were analyzed for a number of trace metals. The silver concentrations measured were less than 0.1 ng m^{-3} for an urban background level, while during the high

TABLE 4.4 SUMMARY OF BACKGROUND AEROSOL SILVER CONCENTRATIONS*

DATE	TREATMENT	TIME	ALTITUDE im MSL	AREA	Ag Conc. ng ml^{-1}
1/27/76	non-seeded	AM	3810	SE of Den	0.5 ± 0.5
		AM	3840	S of Den	< 0.1
		AM	4270	S of Den	< 0.1
		AM	4270	SE of Den	< 0.1
1/27/76	non-seeded	PM	3810	SE of Den	1.0 ± 0.5
		PM	3810	S of Den	< 0.1
		PM	4270	S of Den	< 0.1
		PM	4270	SE of Den	< 0.1
1/26/76	non-seeded	AM	3810	SE of Den	< 0.1
		AM	3810	S of Den	< 0.2
		AM	4270	S of Den	< 0.1
		AM	4270	SE of Den	< 0.2
1/26/76	non-seeded	PM	3810	SE of Den	< 0.1
		PM	3810	S of Den	< 0.2
		PM	4270	S of Den	< 0.2
		PM	4270	SE of Den	< 0.2

*All concentration were corrected for IASS wall losses after Mulvey and Shaeffer (loc. cit.).

pollution period the concentration was measured at between 2.2 and 2.3 ng m^{-3}. A study by Harrison et al. (1971), use the same analytical technique measured, among other things, silver trace metal concentrations collected at ground level from the East Chicago, Indiana, and Niles, Michigan areas. Their results showed silver concentrations varying from 5 ng m^{-3} in a heavily industrialized area to 0.5 ng m^{-3} in a nearby suburban environment. Measurements of trace element concentrations in the San Francisco Bay area were made by John et al. (1973) on a case study basis. Their results showed silver concentrations to range from 0.05 to 0.2 ng m^{-3}.

Background silver aerosol concentrations were measured at rooftop level in the city of Fort Collins during the winter of 1973 (Brier and Grant, 1973). The results, after adjusting for a difficulty in the analytical technique (Schaeffer, 1976) exhibited concentrations averaging 0.018 ng m^{-3}. Limited aircraft observations of background silver aerosol concentrations were conducted in the National Hail Research Experiment area (NHRE) located in northeastern Colorado. Of the 16 samples collected during the three aircraft flight days, nine samples had concentrations below the detection limit of 0.6 ng m^{-3}. The measured concentrations ranged from 7.2 to 0.6 ng m^{-3}. A spot surface measurement made in the mountains just west of Fort Collins over a long period of time (48 hours) indicated a normal background concentration of 0.011 ng/m^3 ($\pm$ .006 ng/m^3).

4.1.2 Seeded Day Levels of Ice Nuclei and Silver

The days which were seeded in the present study naturally divide themselves into three general cases. In Case 1 there was no cloud over the main target site at Climax (the 3 and 4 January 1975 period). This specific case represents the class of experimental days when the forecast was wrong (i.e., no weather modification potential existed). Case 2 is one when a low orographic cloud was present for some part of the experimental unit and limited precipitation occurred during the period (16-17 January 1975). This case is included in the class of days which were marginal. A marginal modification potential did exist on the experimental day but either insufficient moisture and/or vertical motion were present to sustain a vigorous precipitating cloud system. Case 3 is one when a low cloud was present during the experimental unit and precipitation occurred over a substantial portion of the period of such as 20-21 December 1974 and 4-5 February 1976. This case represents that class of days when the forecast was verified and a large modification potential existed. Thus a spectrum of possible seeding events was covered. It should also be stated that it was possible for all three conditions to exist for a period of time during a specific experimental unit.

4.1.2.1 <u>Case 1. No Cloud Present</u>

This class of days represented by the 3-4 January 1975 is a case of clear air transport. On 3 January at 8 am the seeding generators were started. A cloud layer with a true ceiling at 1220 m AGL was reported at 8 am* but dissipated by the 11 am observation time. The next cloud cover reported was at 8 am on 4 January (no ceiling reported). No precipitation was observed or recorded. Reliable IN data was not available from the Queenaire for 3 January. The 500-B, however, was able to collect ice nuclei data at the 3050, 3600 m and 4050 m levels.

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*Unless otherwise stated, mountain observations of present weather conditions were made at Leadville, Colorado by NOAA personnel.

The flight tracks and ice nuclei concentration measurement are shown in figure 4.5. From the aircraft data it is very clear that extremely high concentrations of ice nuclei in comparison to background were leaving the Climax region. Concentrations from 24 to over 700 per liter were recorded. Low level (3050 m) observations show lower concentrations. This indicates the upper level observations are not of an inadvertant anthropogenic origin. The general pattern is one of high concentrations on the northern and southern sections of the tracks with relatively low (<100 No. ℓ^{-1}) concentrations in the center of the tracks. The 3600 m flight track seems to have large sections of the flight with the highest concentrations. The general plume structure appeared to exhibit a wave pattern with respect to the flight level (constant pressure surface). The highest concentrations appeared to pass through the flight level. The plume appeared very irregular, as one might expect after a transit of 100 km over mountainous terrain. Visual observations from the aircraft confirmed that there were some orographic clouds of a wave and lenticular nature over the mountains. Observiations of IN taken at Greenland 7NE show no above-background concentrations throughout the day. The average concentration was less than 1.0 No. ℓ^{-1}. There were no low level clouds over the eastern plains on this day.

4.1.2.2 <u>Case 2. Weak Clouds Present</u>

The experimental day of 16-17 January 1975 is divided into two classes of observations. Those on 16 January were conducted while clouds were present over the Climax region, both before and after the generators had been turned on, and when precipitation was not falling. The observations on 17 January were again made while clouds were present over

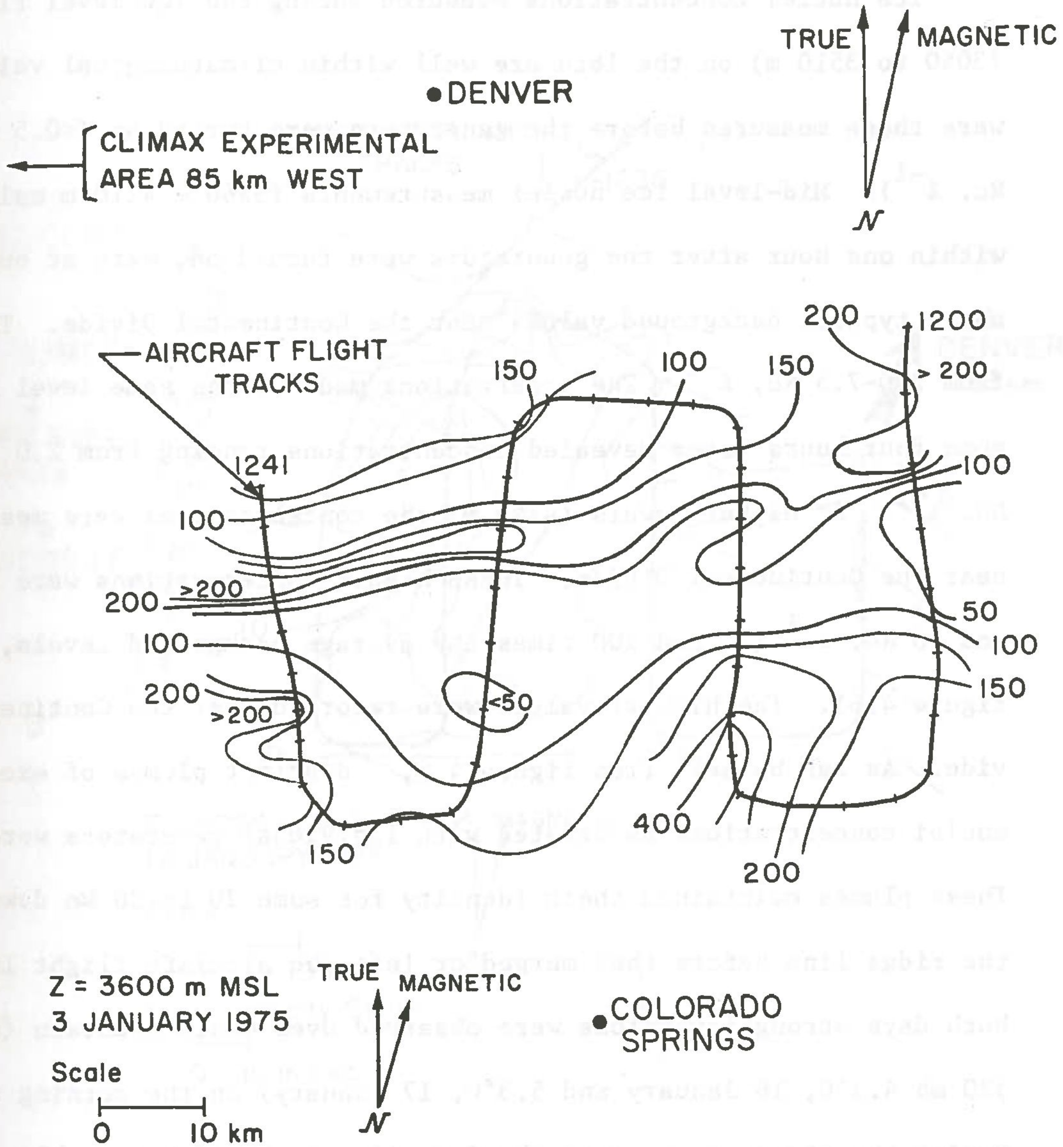

Figure 4.5. Aero Commander flight tracks and ice nuclei concentrations ($N_0 \ell^{-1}$ active at -20°C).

Climax, precipitation had stopped in the target region, and the generators had been off for 3.75 hours.

Ice nuclei concentrations measured during the low level flights (3050 to 3510 m) on the 16th are well within climatological values, as were those measured before the generators were turned on (<0.5 to 1.5 No. ℓ^{-1}). Mid-level ice nuclei measurements (3960 - 4110 m msl) made within one hour after the generators were turned on, were at our slightly above typical background values near the Continental Divide. They ranged from 2.0-7.5 No. ℓ^{-1}. The observations made at the same level downwind some four hours later revealed concentrations ranging from 2.0 to 24 No. ℓ^{-1}. At higher levels (4720 m) the concentrations were measured only near the Continental Divide. These higher concentrations were between 5 and 40 No. ℓ^{-1} (10 and 100 times the average background levels, see figure 4.6). The highest values were recorded near the Continental Divide. As can be seen from figure 4.6, distinct plumes of excess ice nuclei concentrations associated with individual generators were observed. These plumes maintained their identity for some 20 to 30 km downwind of the ridge line before they merged or left the aircraft flight level. For both days strong inversions were observed over Chalk Mountain (around 520 mb 4.2°C, 16 January and 5.3°C, 17 January) on the morning ascent. During the afternoon ascents the inversion weakened but stable layers still persisted.

Flight observations on the 17th showed a somewhat similar pattern to the 16th except the spacial features of the plume were more varied with concentrations varying from .5 to 60 No. ℓ^{-1}. Concentrations at lower altitudes (4720 m) were close to background values.

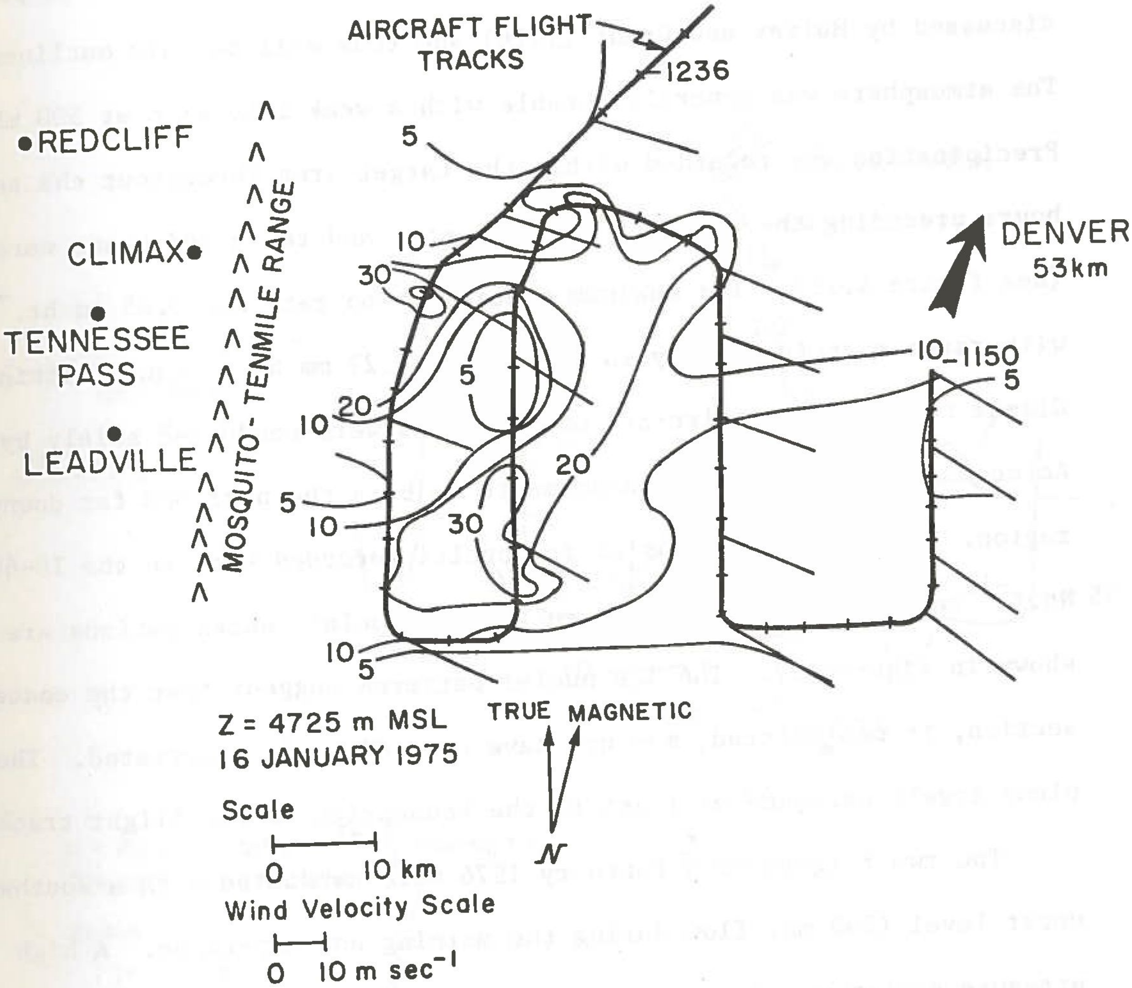

Figure 4.6. Queen Air flight tracks, ice nuclei concentrations (at -20°C) and the aircraft measured windfield.

4.1.2.3 Case 3. Precipitating Clouds Present

The final class of events, namely, those when precipitation was occurring at the target during seeding, is represented by the 20-21 December 1974 and the 5 February 1976 cases. The first case was previously discussed by Mulvey and Grant (1976) and thus will be only outlined here. The atmosphere was generally stable with a weak inversion at 500 mb. Precipitation was recorded within the target area throughout the seven hours preceding the aircraft measurements, and the cloud bases were low (see figure 4.12). The maximum precipitation rate was 3.05 mm $hr.^{-1}$ with rates most frequently in the .25 to 1.27 mm $hr.^{-1}$ range within the Climax target area. Aircraft observations were conducted solely by the Aerocommander which made measurements in both the near and far downwind region. The concentrations of ice nuclei recorded were in the 10-60 No. $No.\ell^{-1}$ range. The flight pattern and ice nuclei concentrations are shown in figure 4.7. The ice nuclei patterns suggest that the concentrated section, if one existed, may not have been directly penetrated. The plume itself extended at least to the boundaries of the flight track.

The two flights of 5 February 1976 were conducted with a southwesterly upper level (500 mb) flow during the morning and afternoon. A high pressure system pushing southeastward along the eastern slope of the Rocky Mountains caused an intense upslope storm to form on 3 February 1976 and last through 5 February 1976. During the observation period, the low level cloud was capped by a 15 to 20°C inversion. An upper level cloud formed during the morning and precipitated during the afternoon. This cloud, together with the lower upslope cloud, formed a classical "seeder-feeder" system. During the aircraft penetrations of the upper

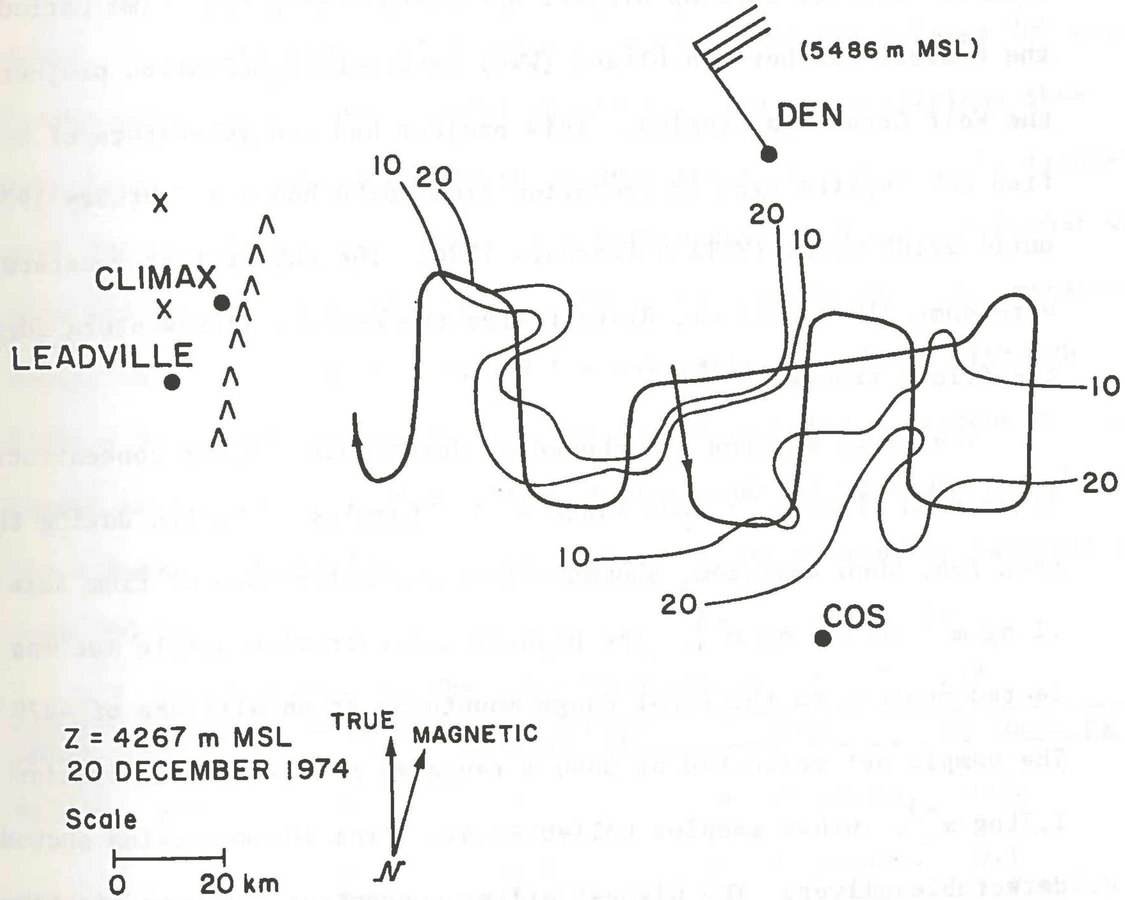

Figure 4.7. Aero Commander flight tracks and ice nuclei concentrations ($N\ \ell^{-1}$ at -20°C).

level cloud on the afternoon run, graupel particles were observed and about 6 mm of clear rime ice was accreted on the IASS.

The seeding generators were in operation in the Climax region but due to the south-southwesterly upper level flow, it is unlikely that the seeding material from Climax could have reached the aircraft flight tracks. Another seeding project operating during this time period was the Western Weather Consultant (WWC) snowpack augmentation project in the Wolf Creek Pass region. This project had ten generators of a modified CSU Skyfire type in operation from 10:00 hours 4 February 1976 until 22:00 hours (MST) 6 February 1976. The WWC project generators were some 210 to 245 km. distant from the extreme southwestern edge of the flight tracks.

The early morning run showed no detectable silver concentrations (less than .1 ng m^{-3}) (see Table 4.5). Samples collected during the afternoon run, when analyzed, showed silver concentrations of from less than .1 ng m^{-3} to 5.8 ng m^{-3}. The highest concentration sample set was collected nearest to the Front Range mountains at an altitude of 4270 m. The sample set collected at 3660 m revealed a silver concentration of 1.7 ng m^{-3}. Other samples collected away from the mountains showed no detectable silver. The highest silver concentrations were six times higher than the highest background concentrations observed. The ice nuclei concentrations measured at the same time ranged from less than .5 to 62*No. ℓ^{-1}. The pattern formed by the excess ice nuclei concentrations strongly resembled a plume. The orientation of the "plume" was primarily along the general wind. The concentrations observed were within the range of measured urban silver levels and were about ten times

*One minute averages

higher than the concentrations possible with a clear air transport of seeding material from the generators in operation. This suggests that, although some part of the silver concentrations may be due to seeding, the entire amount cannot be attributed to seeding.

An order of magnitude estimate of the number concentration of active ice nuclei present in the sampling area was made using a Gaussian plume model. The dispersion coefficients were estimated for a class "D" stability using the curves of McMullen (1975). The concentrations thus calculated were reduced by 95% to account for losses during the transport through the target cloud. This percentage is in line with what was measured by Orgille et al (1971). The final results were concentrations almost equal to those observed by the aircraft. The data, although limited in quantity, suggest that the excess ice nuclei concentrations (above background) were due to the seeding material released near Wolf Creek Pass. This implies a long-range transport of seeding material of over 200 km.

4.5 TRACE AEROSOL SILVER CONCENTRATIONS ON A SEEDED DAY*

DATE	TREATMENT	TIME	ALTITUDE (m MSL)	AREA	Ag conc. ng m^{-3}
2/5/76	seeded	AM	3810	SE. of Denver	<0.1
		AM	4270	S. of Denver	<0.1
		AM	4270	SE. of Denver	<0.1
2/5/76	seeded	PM	3810	SSE. of Denver	1.7 $\pm$ 0.6
		PM	4270	S. of Denver	5.8 $\pm$ 0.7
		PM	4270	SE. of Denver	<0.1
		PM	4270	E. of Denver	<0.1

*All concentrations were corrected for IASS wall losses after Mulvey and Shaeffer (loc. cit.).

4.1.2.4 General Comments

Since most aircraft observations of background ice nuclei concentrations were in the .5 to 1 No.ℓ^{-1} range over the mountains, concentrations in excess of 10 No. ℓ^{-1} may safely be considered to be due to generator activities. The structure of the seeding plume leaving the target area defined by the 10 No. ℓ^{-1} isoline showed large spacial variabilities. These variabilities may be largely due to the spread of the surface source region resulting from mountain-valley breezes and other mesoscale winds as observed by Reid (1976). The plumes rising over the Continental Divide spread out horizontally, but on occasion it maintained a general concentrated core structure even after moving 50-80 km downwind of the generators.

The most concentrated plumes occurred under clear transport conditions with no clouds over the target. Typical ice nucleus concentrations far downwind of the seeding were in the range of 100-400 No. ℓ^{-1}. The cloudy conditions with occasional light snow allowed the transport of moderate concentrations of ice nuclei in the 10-60 No. ℓ^{-1} range. Moderate precipitating conditions also allowed concentrations between 10 and 60 No. ℓ^{-1} of ice nuclei to be transported to downwind regions. The trends in the observations are generally consistent with expected values in light of silver iodide removal processes associated with precipitation formation. Order of magnitude estimates of particle losses to cloud droplets were made assuming a Brownian diffusion mechanism. Estimates were also made for ice crystal scavenging losses using the efficiency coefficients of Sood and Jackson (1970). The analysis indicated that the majority of losses should be due to the nucleation processes and that about 10% should be due to scavenging processes.

All of the observations discussed were made under generally stable conditions, frequently with elevated inversions. Questions concerning possible photodeactivation could not be addressed in the field experiments due to aircraft flight procedures and instrument uncertainties. A brief review of the subject is given in Appendix A. The above normal background silver aerosol concentrations measured on the afternoon flights of 5 February 1976 cannot be explained in terms of local urban sources. A Gaussian plume model was used as an order of magnitude estimator, even though it is thought to be a poor diffusion model for mountainous terrain. From the model predictions it does not seem likely that seeding activities in Colorado could have produced the silver concentrations observed. Additional trace metal data collected which is beyond the scope of this analysis currently being analyzed suggests regions outside of Colorado as the source of the silver.

4.2 Surface Snow Samples

The snow collection network (see figure 1.1) was designed to gather freshly fallen snow samples for trace silver analysis from treated and nontreated storm systems which occurred over the eastern plains of Colorado. The details of the project are given elsewhere (Mulvey and Grant, 1976). In brief, freshly fallen snow samples were collected by cooperative observers at various sites. The samples were kept frozen until analyzed. The frozen samples were chosen at random by the analyst without any knowledge of whether or not the sample was from the treated or non-treated set. Each snow sample was broken up in the collection bag and well mixed. A portion was then separated off into a smaller size plastic bag. As the sample was melting, the pH of the separated portion was lowered to about 1.5 by the addition of redistilled 3M HNO_3, in order to preclude container wall losses. The completely melted sample was ten micro-pipeted into graphite atomic absorption furnaces. The furnaces were then placed in a Varrian model 63 carbon rod flameless atomizer unit fitted to a Varrian model AA 5 atomic absorption spectrophotometer with a Varrian model BC-6 automatic background correction unit. The furnaces were then heated in a sheath gas of argon and methane to a temperature of 1800°K C. The absorbance was recorded at the analytical wavelength (3280.7° A) on a Perkin-Elmer model 165 strip recorder. Individual calibration curves were established for each furnace using standard solutions of $AgNO_3$ to bracket the absorbance peak. The detection limit of the technique was determined to be .5 x 10^{-12} gm/ml with precision typically of $\pm$ 12% relative standard deviation over the range of concentration of interest. Experiments were performed to determine the solubility of AgI in a 0.03 M HNO_3 solution. The results showed that the solubility was at least two orders of magnitude about the expected concentration. It was therefore assumed that all silver iodide in the acidified melt snow water was in solution.

During Downwind Seed I and II, four seeding projects in the Colorado Rockies were in operation. Two were in the Wolf Creek Pass area and two in the Climax area. Each project was considered to be a possible source of silver for the plains snow and the data analysis provided for such possibilities. The distance to the collection sites from the sources ranged from 90 to 395 km.

The silver concentrations thus measured (a total of 204 samples) formed the basic dependent data set used in this analysis. The data set was dependent because it contained groups of samples from the same storms. To establish an independent data set suitable for statistical investigation, the measurements were divided into a data set from the days on which seeding occurred in the mountains (treated data set), and a data set from the days on which seeding did not occur in the mountains (nontreated data set). The assignment to a treated or nontreated data set was based on collection time, generator location, operation time, and transporting wind velocity. The data groups from each storm in a particular data set were averaged to yield a single independent data point representing the silver concentration in snow for that particular storm. This procedure was followed for both the treated and nontreated data set. Thus, two independent data sets, where each value of a set represented the average silver concentration in snow for a given type of storm (treated vs. nontreated), were formed. This reduced the number of samples to 14 and 47 for the treated and nontreated sets, respectively. A summary of the results of these measurements is shown in figures 4.8 and 4.9.

The independent data sets were statistically tested to determine if they were from the same overlying distribution using a Kolomogro-Smirnov test and a sum of the R^{th} powered rank test. The Kolmogorov-Smirnov test is a non-parametric test of like populations, and was performed using the observed cumulative frequency distributions for the two data sets. The formulation of Lidgren (1968) was used where D_T is the test statistic derived from the sample cumulative frequency histogram, and the critical value of the test statistic is given by:

$$\left(-\frac{1}{2}\left(\frac{1}{n_1} + \frac{1}{n_2}\right) \log \frac{\alpha}{2}\right)^{\frac{1}{2}}$$

where α is the significance level and n_1 and n_2 are the sample sizes. The test rejected the null hypothesis (H_0) of like populations at less than the 0.5% level. Upon inspection of the cumulative frequency distribution it appears that the difference between the two data sets is due in part to a location change.

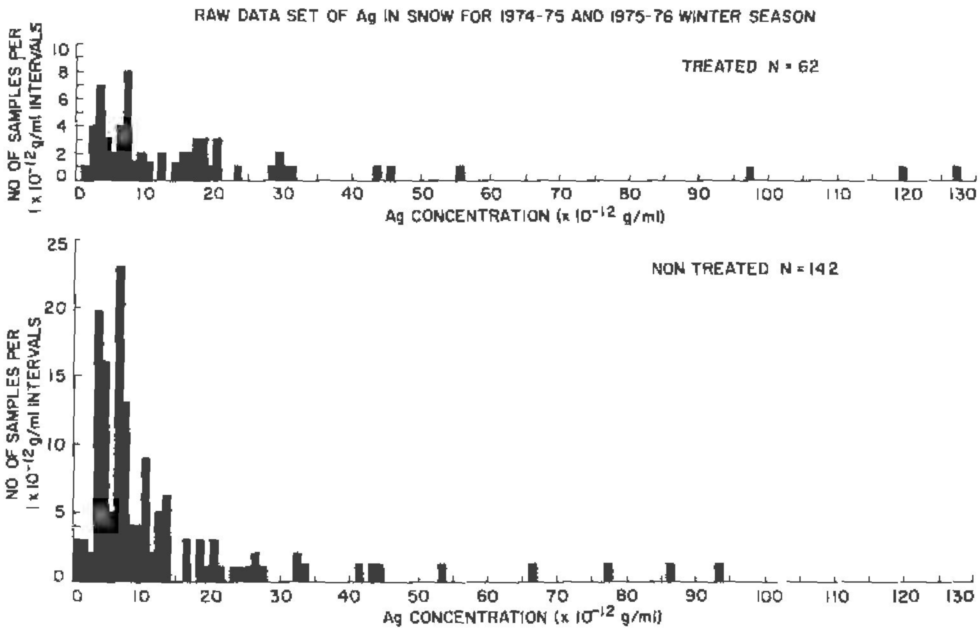

Figure 4.8. Raw silver concentration in snow data set.

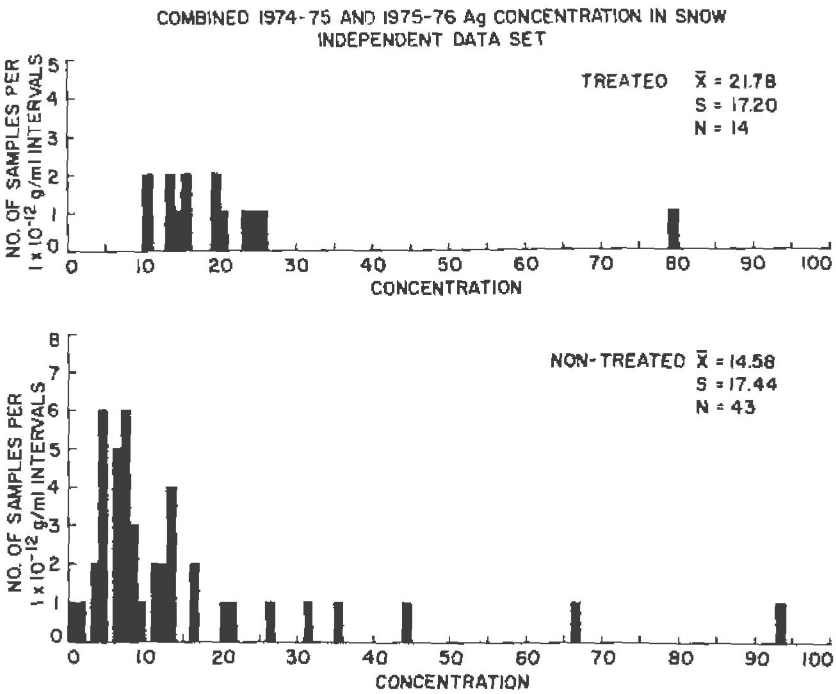

Figure 4.9. Independent silver concentration in snow data set.

Table 4.6. Probabilities for a normally distributed variable (X) with a mean of 0 and a variance of 1.

X	1.0	1.5	2.0	2.5	3.0	3.5
P(|X| > x)	0.317	0.134	0.045	0.012	0.003	<0.001

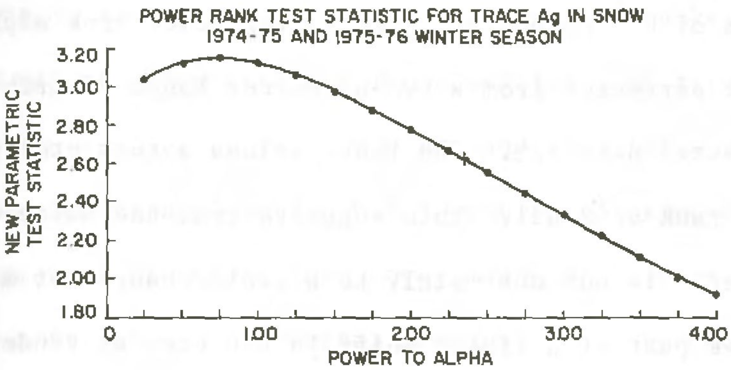

Figure 4.10. Test statistics for the independent silver concentration in snow data set for various powers.

The second class of statistical tests used, namely, the sums of the R^{th} power rank test, includes the Wilcoxon sum rank test at power one and the sum of the squared ranks test at power two. This class of tests was discussed by Mielke (1972). A tie-adjusted formulation of these tests developed by Mielke (1967) was used. The power of ranks was adjusted from 0.25 to 3.00 in increments of 0.25. The results of these tests are presented in figure 4.10. By the use of Table 4.6 it can be seen from the figure that the H_0 was rejected at less than the 5% level for all powers tested. These results can also be interpreted as a test for a scale change as a reason for the differences between the two data sets. An alternate test for scale changes between the two distributions is the sum of R^{th} power rank test to the power rank alpha, where alpha is a scale parameter from a two-parameter Kappa distribution fitted to the nontreated data set. The test yielded a test statistic of 2.628 at the power rank of 2.351. This suggests that the difference bwtween the two data sets is not due mainly to a scale change but more likely due to an additive part of a linear shift in the central tendency (mean) of a distribution, i.e., location change.

The results of the analyses performed on the snow sample data strongly suggest that additional silver was observed in the snow on treated as opposed to nontreated periods, and that the difference between the two distributions is most likely due to a location change. Investigations into possible inadvertant biases in the data set were conducted. Besides the Colorado seeding activity the possible sources of silver investigated were long range transport from outside of Colorado and surface sources in central Colorado.

The long range transport of silver from other anthropogenic or natural sources was investigated using the 500 mb. wind direction observed at Denver on the treated and nontreated days. The vectorially averaged wind direction observed during the 57 storms formed the basic data set. The resultant wind directions, one for each treated and nontreated storm, were compared using a Chi Square test. The analysis failed to reject the null hypothesis that the samples were drawn from the same population. The conclusion was that the wind directions were not significantly different for the treated as opposed to the nontreated storms. This implies that selective transport of silver from far distant sources probably did not occur during the treated storms.

The central section of Colorado is known to be a key mining region for various minerals and metals. The possibility of silver being transported from the surface of tailing ponds and slag piles in this region to the collection sites downwind was investigated using snow cover data. Composite relative frequency snow cover maps were constructed for the treated and nontreated experimental day set. The observations of 25 climatological stations in the central and east-central Colorado mountains were obtained from NOAA climatological data records and used. The analysis showed that more stations reported snow cover on the treated days than on the nontreated days. This implies that surface to air transport of silver containing particles would be less likely to occur on the treated days. The analysis thus seems to rule out a surface silver transport as a source for the excess silver observed on the treated days. The analyses relating to the possible sources of silver strongly suggest that the seeding operations conducted in the mountains were the source of the excess amounts observed.

4.3 Radar Studies

Radar studies of the characteristics of upslope clouds were conducted during the two years of this investigation with the cooperation of the NOAA radar personnel using the weather radar located at Limon, Colorado. The radar is a 10-cm wavelength WSR-57 noncoherent unit. The radar was operated in a special mode for this experiment. Upon alert from CSU the radar personnel would begin to contour on PPI radar overlays all echoes observed from the MDS level upwards at 6 dBz increments. Additional data noted from both PPI and RHI scans were maximum cloud top, echo area movement, and, occasionally, cell movement and general cloud top echo appearance. A typical overlay is shown in Figure 4.11.

A total of six storms were examined. The average maximum echo top reported was 4685 m msl. Observations made in an RHI scan mode showed that the tops were frequently uniform. Since the first echoes of a given storm were not always observed due to personnel shortage and other limitations, the area coverage of the echoes were analyzed.* Composite frequency maps were constructed from echo areas with returns greater than -109 dBm and with returns greater than -103 dBm. A grid work of planer boxes approximately 30 km x 30 km was constructed. If 30% or more of the grid box was within a return contour an echo was recorded for that box.

The map for returns greater than -109 dBm showed a roughly symmetrical pattern about the radar site with an elongated section to the ESE. This pattern was not unexpected since beam filling problems and beam elevation increases would tend to reduce the probability of detection of

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*For the purposes of these analyses no distinction between seeded and nonseeded storms was made.

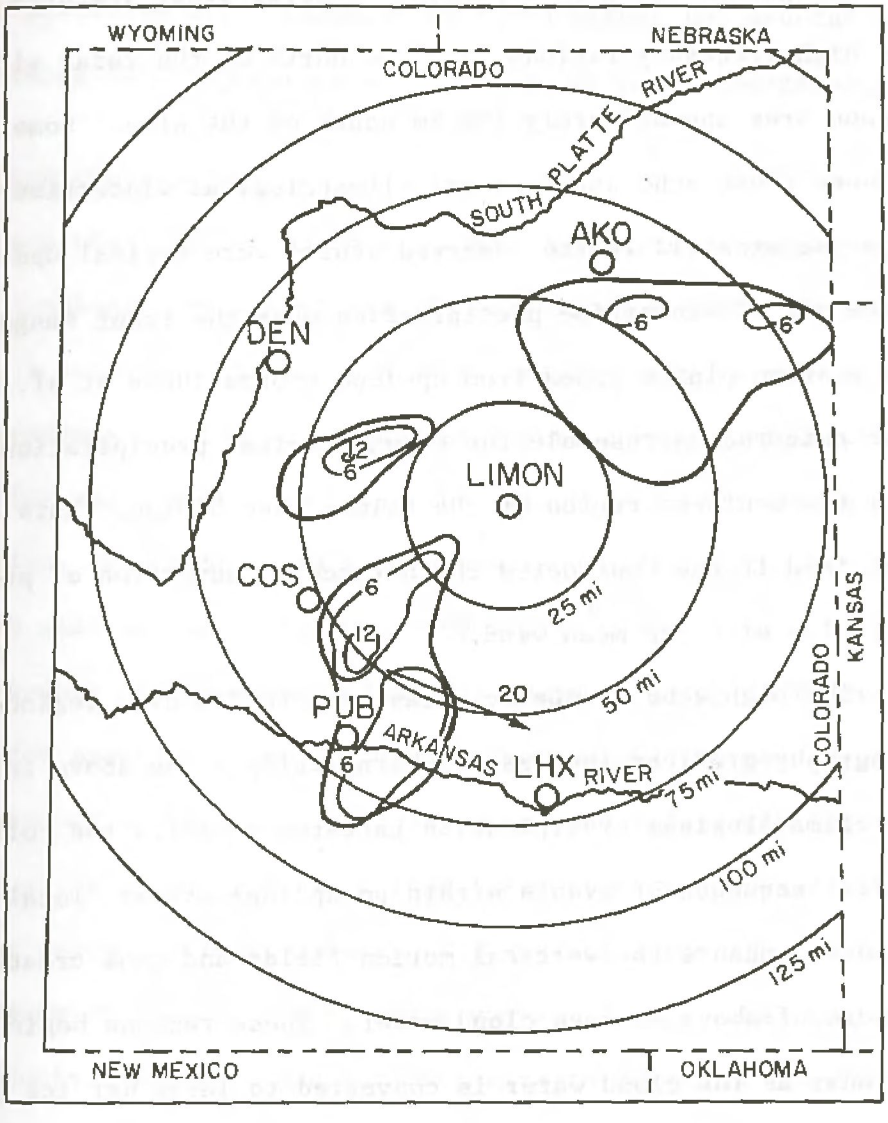


Figure 4.11. Typical radar returns from an upslope cloud (16 January 1975, 2230 MST) contours are every 6 dBz above the minimum detectable signal.

precipitable particles as the range increased. Since the cells themselves migrate within the upslope cloud system, generally to the east, the elongation was also expected. Several other features observed were two high frequency regions, one due north of the radar site, and the second area approximately 100 km south of the site. Some correlation between these echo patterns and climatological wintertime precipitation maps was expected if the observed storms were typical upslope storms since 90% of wintertime precipitation over the Front Range and eastern plains comes from upslope storms (Henz et al., 1976). The echo patterns do resemble the climatological precipitation maps, except over the southern region of the Palmer Lake Divide. This anomaly can be explained if one considered the horizontal advection of precipitable particles with the mean wind.

The high echo frequency areas seem to lie over regions where the topography gradient increases substantially. The above facts along with the climatological precipitation patterns suggests the following as a logical sequence of events within an upslope storm: local topographic features enhance the vertical motion fields and thus create localized regions of above average cloud water. These regions begin to show up on radar as the cloud water is converted to large wet ice particles. The enhanced vertical motion regions begin to precipitate as the elements move within the upslope cloud with the mean wind. The precipitation which reaches the surface at some distance from the genesis areas constitutes an additional percentage of the precipitation above that due to the more stratiform section of the cloud. The data collected can thus be seen to be consistent with the climatological precipitation patterns. Although the soundings for typical upslope storms show little convective instability, the strength and range of the radar returns suggest that convective-like cells with some liquid cloud water and wet rimed ice particles are frequently embedded within the general upslope clouds. These cells appear to be triggered by local topographic features.

4.4 Surface Observations

Surface observations and ice nuclei concentration measurements were made at Greenland 7 NE during the 1974-75 winter season. Data was collected on a total of six days (three events). The data show that there is some tendency for higher ice nuclei counts during periods when seeding material was expected to be in the region, but the results are inconclusive. Concentrations observed were usually in the 0-5 No. ℓ^{-1} range with some spikes up to 20 and 80 No. ℓ^{-1}.

An example of the Greenland surface data is shown in figure 4.12. The high ice nuclei concentrations observed during the seeded period occurred in conjunction with overcast skies and relatively low ceilings. This type of data was typical of that taken at this downwind site. The ice nuclei concentrations, however, did exhibit large fluctuations over short periods of time. This behavior was not due to local contamination. Too few observations were made at this site to determine local background levels and therefore determine if the high concentrations were due to background fluctuations or due to seeding material reaching the surface.

The surface weather observations from several national network stations were used to supplement the aircraft and radiosonde observations. Based on these surface observations the seeded days were assigned. to either case 1, 2, or 3. A sample of the data received from the surface stations is shown in figure 4.13. For this period, 20-21 December 1974,

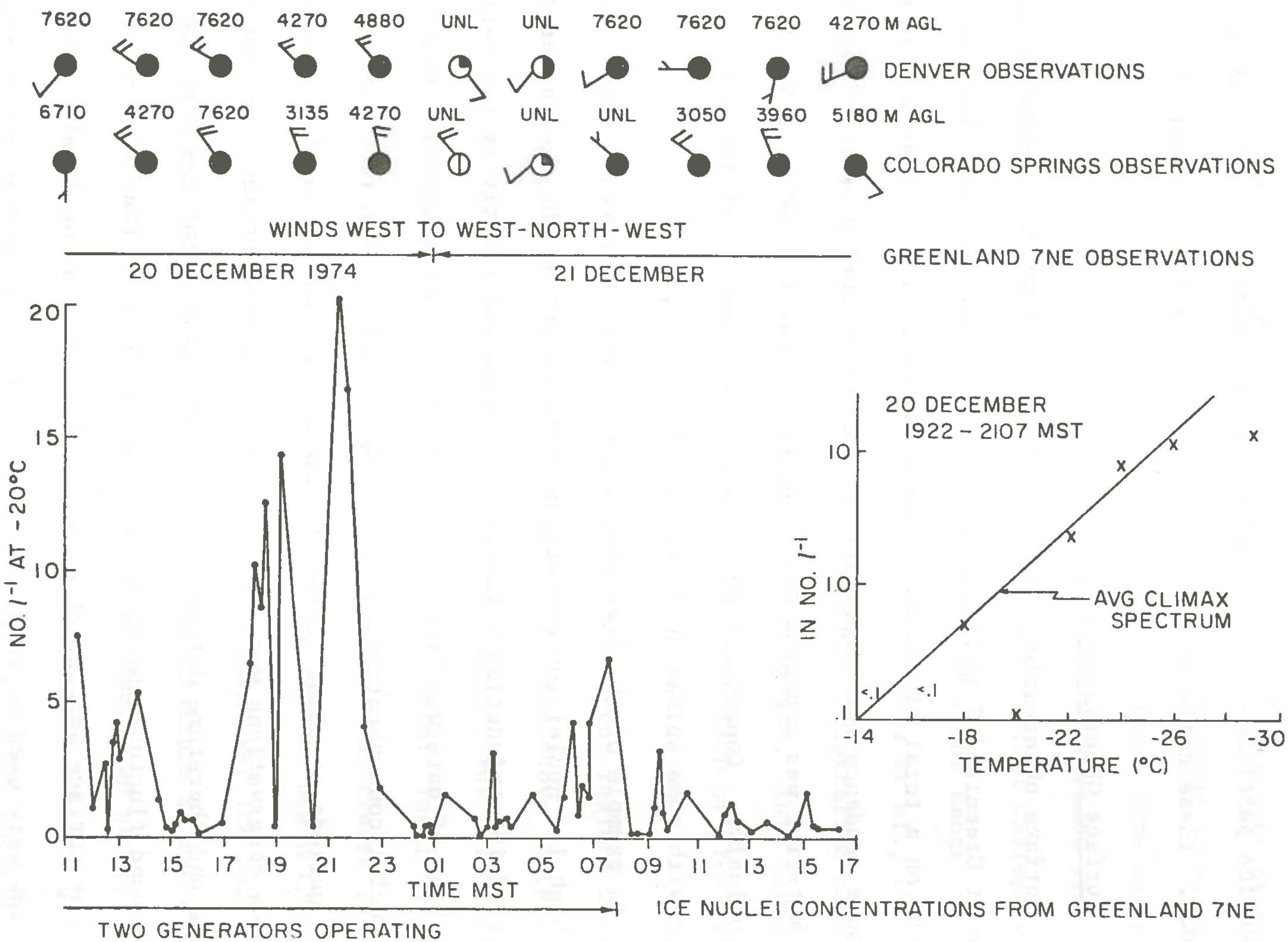


Figure 4.12. Typical surface observations and measurements (20-21 December 1974).

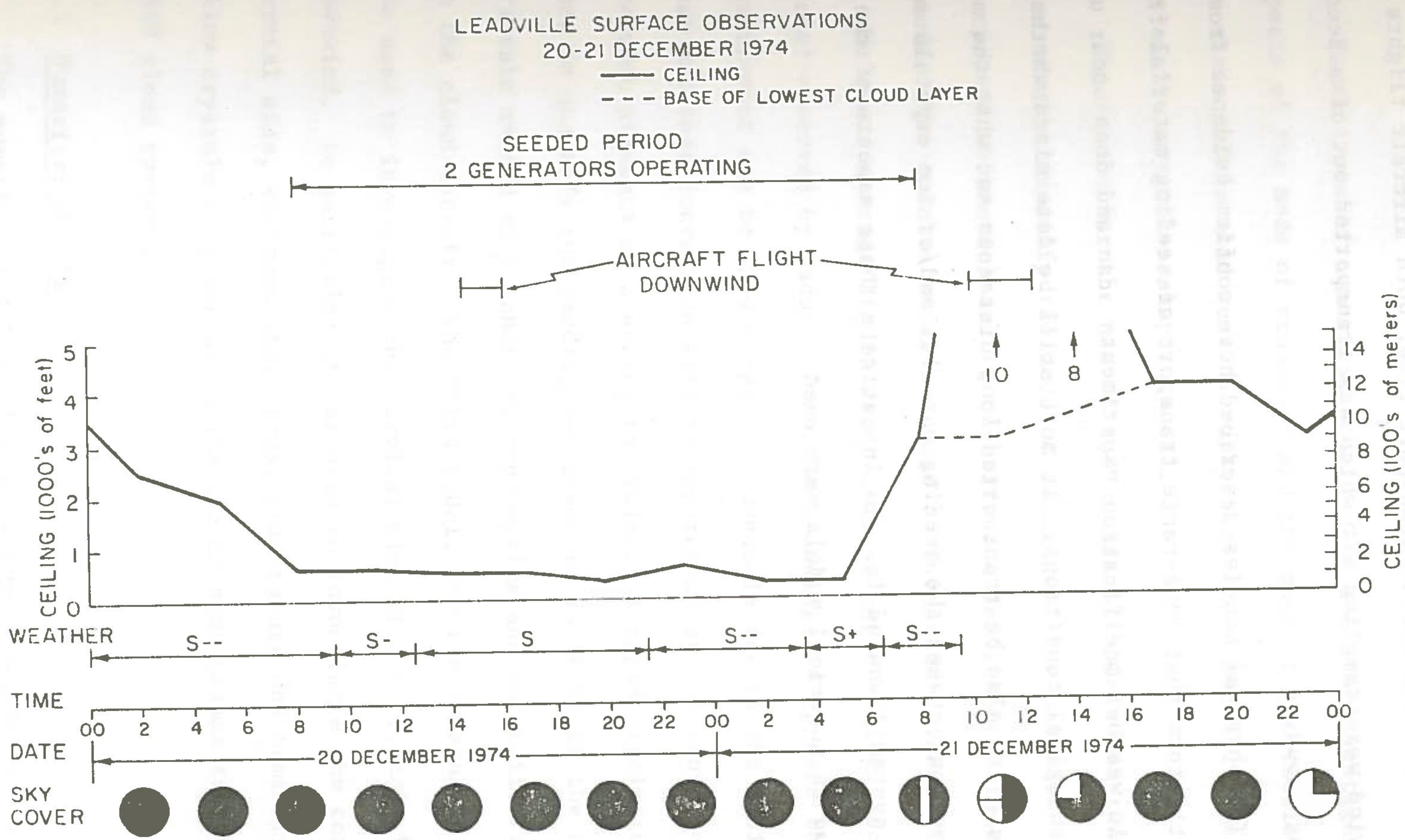


Figure 4.13. Typical Leadville surface observations.

snow was falling and low clouds were present in the target area during the entire period of seeding operations. The diagram shows that if one allows for a reasonable transport time, both aircraft flights conducted downwind were sampling air which was transported out of a seeded precipitating cloud.

The physical studies described here confirm evidence from previous investigators that long-range transport of seeding material from orographic weather modification experiments can and does occur under certain meteorological conditions. It must still be determined whether ice crystals can also be transported long distances and what the mode of interaction between the seeding material and/or ice crystals and the cloud system downwind is. To investigate these aspects of the problem, a group of numerical models were used.

CHAPTER V

NUMERICAL INVESTIGATIONS

Three types of numerical models were used to investigate various aspects of the mode of transport and the mode of interaction. Two of the three models used were microphysical cloud models. The third model was an ice crystal transport model.

The reason for the use of the numerical models was two-fold. They were used to identify the mode of seeding of the downwind clouds (dynamic as opposed to static) and to quantify the seeding requirements of such clouds. The cumulus model was used to investigate the nature and behavior of the above average liquid water content regions (i.e., convective regions) observed by radar. From the soundings it appears that the cloud environment may be only marginally unstable due to the addition of latent heat and that convection will be suppressed at the cloud top due to the frequent presence of a strong inversion. A rapid glaciation model was used to quantify the seeding requirements in terms of the number of ice crystals needed to balance the consumptive and generation rates of water in the cloud updraft. The third model, the ice crystal transport model, was used to investigate the survival time of ice crystals being advected downwind. In particular it was used to investigate the conditions of crystal size, environmental winds, temperature and humidity which would allow crystals originating in the clouds near Climax to reach the downwind cloud systems.

5.1 Numerical Models

The numerical model which was used to investigate the mode of interaction was basically a detailed microphysical model. The model used was

Cotton's "ID" steady state cumulus model (Cotton, 1972 a, b). From the results of the application of this model to typical upslope storm cases, the mode of seeding (interaction) can be determined.

As previously described, the topography of the area extending from the Colorado-Kansas border to the Front Range Mountains is not homogeneous but exhibits several irregularities. Some of these topographic irregularities are capable of enhancing the already present large scale topographically induced vertical motion field. Since the enhancement of the vertical motion field on convectively unstable days could trigger convective development, one would expect to see regions of favored cloud development or a local intensification of the cloud already present. The limited radar data presented in a previous section supports this reasoning of preferred convective activity with areas of intensified topographic lifting. The location of these variations in cloud structure will, of course, depend on the atmospheric stability, the low level wind velocity, the large scale vertical motion field, and the local moisture field. The divisions in cloud structure between embedded convective and stratiform represent different precipitation enhancement potentials and thus require a different numerical simulation. The "ID" cumulus model was used to simulate the processes in the convective regions while a modified form of a rapid glaciation model was used to simulate the microphysical processes occurring in the more stratiform sections of the cloud.

The basic hypothesis underlying most cold orographic cloud seeding experiments is that the inefficiency of the precipitation processes within the cloud is related to a lack of active ice nuclei in concentrations sufficient to consume the liquid water generated by the updraft. Thus, if additional active ice nuclei are injected in concentrations necessary to consume an additional amount of liquid water, the cloud will increase its efficiency by increased precipitation. This, is also the basic hypothesis put forth for extra-area effects from Climax based on the results of the "ID" cumulus model predictions. To estimate the additional number of ice nuclei necessary to increase the upslope cloud to maximum efficiency a modified form of the model developed by Jiusto (1974) was used.

5.2 "ID" Steady State Cumulus Cloud Model

The effects of seeding material on the embedded convective regions within the upslope cloud system were investigated to determine the mode of interaction, that is, dynamic as opposed to static seeding. The model used was a "ID" steady state detailed microphysical model. In this model, the dynamics are parameterized through a constant entrainment coefficient. The microphysics are also parameterized and allowed to interact with the cloud dynamics. The microphysical parameterization of the model uses five phase components in the moisture budget calculations. These components are: water vapor, liquid cloud water, liquid rain water, frozen rain water, and ice crystals. The initial cloud droplet distribution was approximated by a continuous function (Gamma Distribution). The cloud droplets were allowed to grow via condensational and collision-coalesence processes.

Ice crystal nucleation was accomplished using a twenty-one interval temperature dependent scheme for depositional nucleation. Ice crystal growth was also initiated by a parameterized droplet freezing process. Depositional as well as riming (accreational) growth modes were simulated using crystal capacatance and accreational growth equations respectively.

The raindrops and frozen rain were both assumed to have a Marshall-Palmer (1948) type distributions. This assumption allowed the growth equations to be solved in terms of the average particle characteristics. Precipitation was allowed by removing the tail of the particle distributions which had terminal fall velocities greater than the updraft velocity.

The model simulates the first rising "bubble" or element of air of a cumulus cloud. It was from calculations concerning the rising elements that the dynamic seedability was assessed.

The model has some shortcomings in attempting to simulate convection within a stratiform cloud. Although air entrained into the cloud does retain certain environmental properties (i.e., temprature and vapor mixing ratio) the entrained air does not retain the water or ice content of the stratus cloud. The effect of the entrainment of clear air rather than air with cloud particles would be the same for the two types of cloud cases simulated. The effect would be to dry out and cool the cloud. The drying out of the cloud would be accomplished in the initial mixing phase if the air was subsaturated. During this phase the crystals from the stratus cloud would not be available as moisture sources. The drying out would be accomplished in any case by the withholding of the ice crystals of the stratus cloud from the ice water content of the convective cell. The cooling of the cloud would be accomplished in the subsequent growth stages after the initial mixing. In these stages a potential source of growth and therefore warming through the associated latent heat release would be omitted.

The input parameters required by this model and the values assigned are given in Table 5.1.

Table 5.1 Input Parameters used for "1D" Cumulus Model

Parameter	Value	Source
Environmental Sounding	*	National Weather Service Radiosonde Data Denver, Colorado
Cloud Base	*	Environmental Sounding
Cloud Radius	100, 500 and 1000 m.	values assumed
Initial Updraft Velocity	50 cm sec^{-1}	value assumed
Initial Temperature Excess	0.0°C	value assumed
Virtual Mass Coefficient	0.5	Turner (1969)
Entrainment Coefficient	0.2	Turner (1963)
Ine Nuclei Activity Spectrum	**	non-seeded, Chappell (1970) seeded, assumed
Mean Cloud Droplet Radius	4.0 μm	Borovikov et al (1961)
Cloud Droplet Population Dispersion	0.25	Borovikov et al (1961)
Initial Liquid Water Content	0.15 g m^{-3}	Borovikov et al (1961)
Cloud Droplet Number Concentration	250 number cm^{-3}	Zalabsky and Twomey (1974)

* AS per case study

** as appropiate for seeded and non-seeded study

The input parameter of the cloud base and how it was determined required additional clarification. The cloud base was set at the lowest level of the moist layer where the dewpoint depression was equal to 5°C. The cloud base height thus determined was not significantly different from the lifting condensation level (LCL) determined from the sounding. The temperature at the base level determined from the dewpoint depression spread method was slightly warmer than that suggested by the LCL calculations.

The days chosen were taken from upslope events of the 1974-75 winter season. The four cases used were divided into two general types based on the environmental sounding. The first type, represented by 20 December 1974 and 10 January 1975 were days when the radiosonde did not penetrate any water saturated sections of the cloud. The more active sections of the cloud were toward the east.

The second type, represented by 16 and 17 January 1975 and 21 January 1975 were days when the radiosonde penetrated the water saturated sections of the cloud. The reason for separating the data from those days was that the differing responses of weaker clouds (type 1) and stronger clouds (type 2) needed to be tested. Type 1 represents those sections of the cloud where the triggered convection could be dominant. Table II represents those sections of the cloud where considerable liquid water already existed before convection was initiated.

The model was run for three different cloud radii and for three levels of seeding. The seeding levels corresponded to 1, 6 and 50 active ice nuclei per liter active at -20°C with exponential distribution similar to that of Chappell (loc cit.). The results for type 1 clouds showed no cloud top height difference between the natural and seeded cases (see figure 5.1). The moderately seeded case showed little growth past the top heights of the other groups for the three radii tested. The smaller radius clouds showed smaller heights increases (see figure 5.1). These cloud top heights are still far below the cloud top height of the upslope cloud as estimated from the Denver radiosonde. The soundings for these days are shown in figure 5.2 a, b, c and d.

The results for type II clouds of equal radii showed no difference among any of the three levels of seeding. The convective clouds did not even reach the top of the general upslope cloud.

These results suggest that for moist vigorous sections of the upslope cloud the mode of interaction is primarily static. That is, any additional ice nuclei or ice crystals entering the clouds promote more efficient "cloud water" to "precipitation water" conversion and cause little dynamic enhancement of the cloud.

The results of the "ID" cumulus models for type I clouds suggest a very modest cloud top increase which may be from 51 to 99 m. The cells within a weak section of the upslope exhibit some minimal dynamic enhancement. The predictions for type II clouds show no dynamic enhancement at low or moderate seeding levels. This indicates that the main precipitation increase will come from a static seeding mode.

5.3 Rapid Glaciation Cloud Model

A modified form of the rapid glaciation model of Jiusto (1973) was used to investigate the seeding requirements of upslope clouds. The cloud modeled was that suggested by Whiteman (1973). The changes in the Jiusto model were confined to the numerical method and the partially-rimed crystal radius used in the calculations. The so-called improved

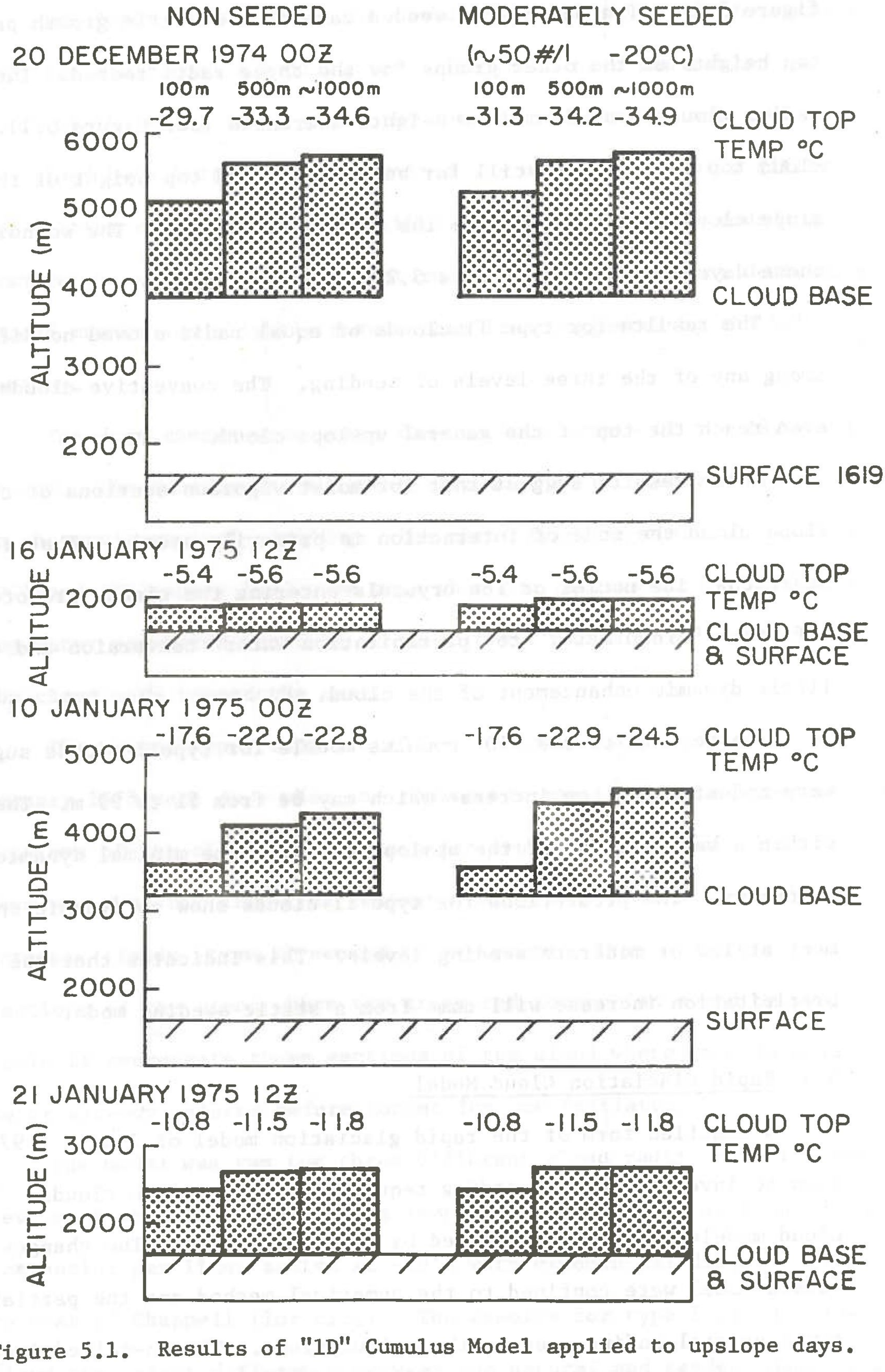


Figure 5.1. Results of "1D" Cumulus Model applied to upslope days.

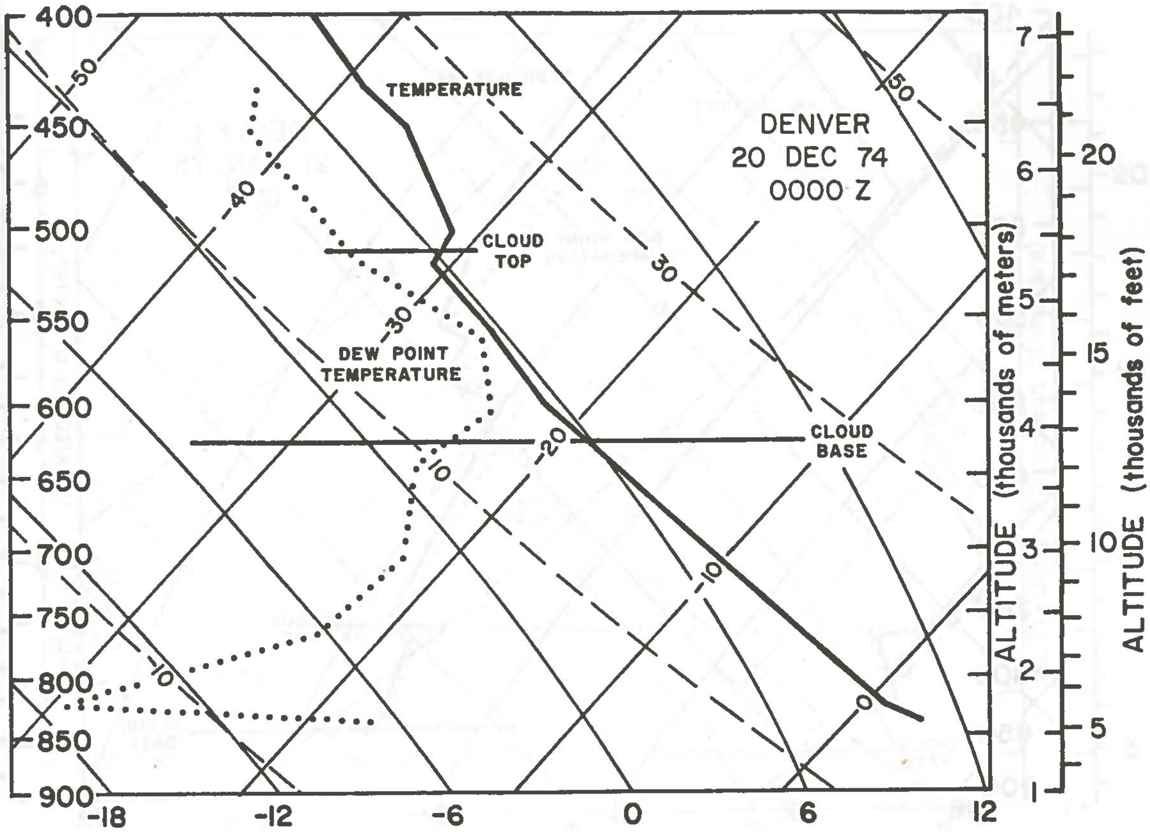


Figure 5.2a Environmental Sounding for "1D" Cumulus Model Runs. Assumed cloud bases and non-seeded model predicted cloud top height are shown.

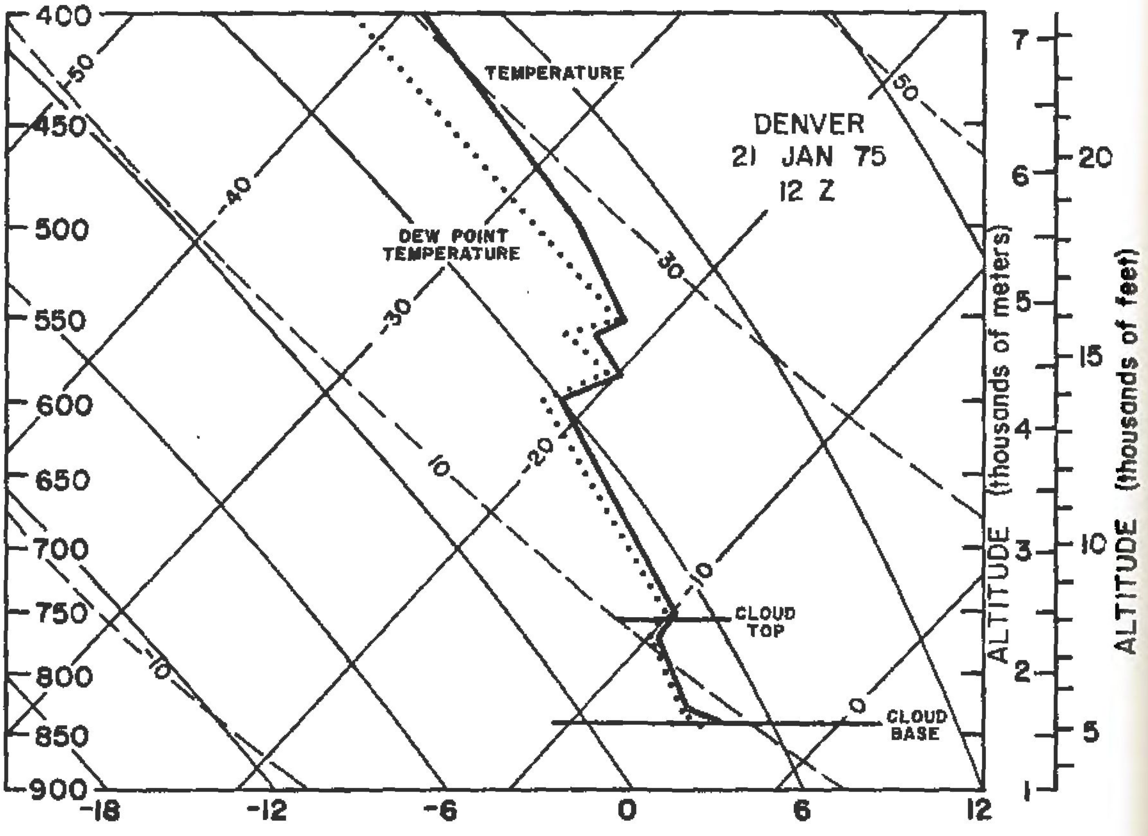


Figure 5.2b Same as Figure 5.2a

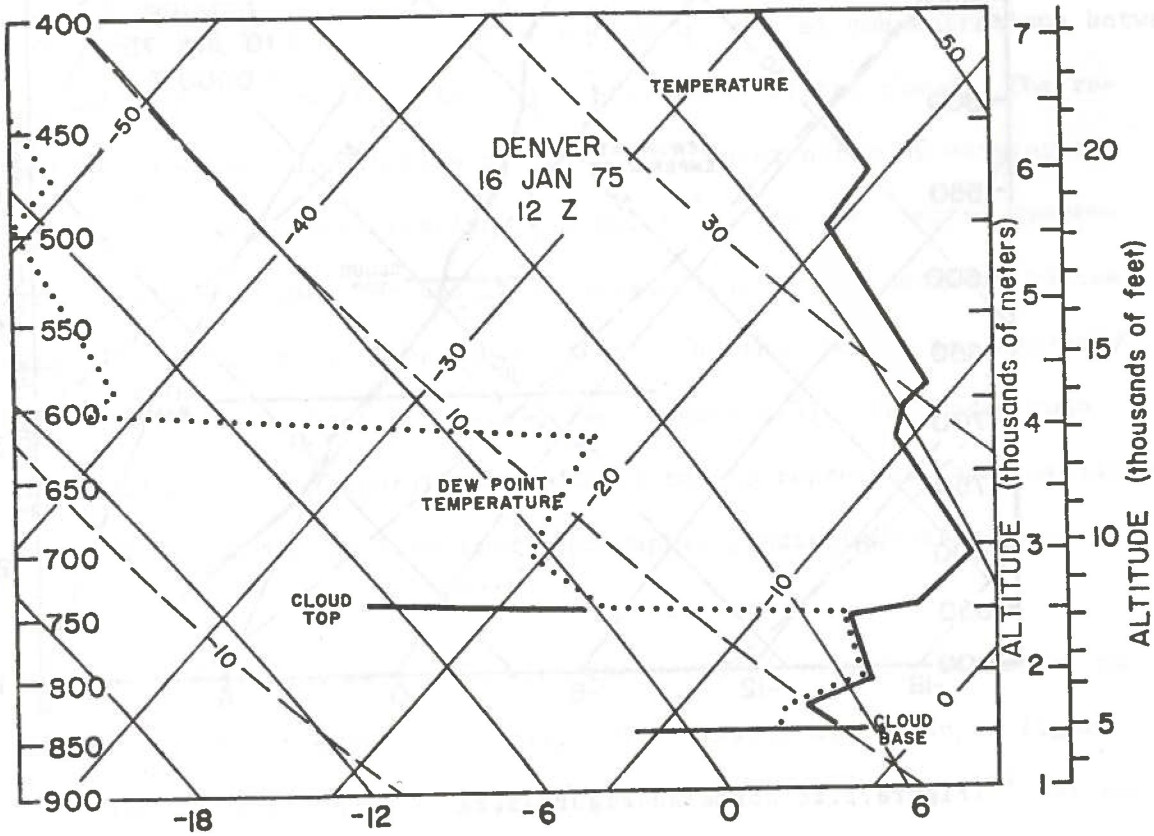


Figure 5.2c Same as Figure 5.2a

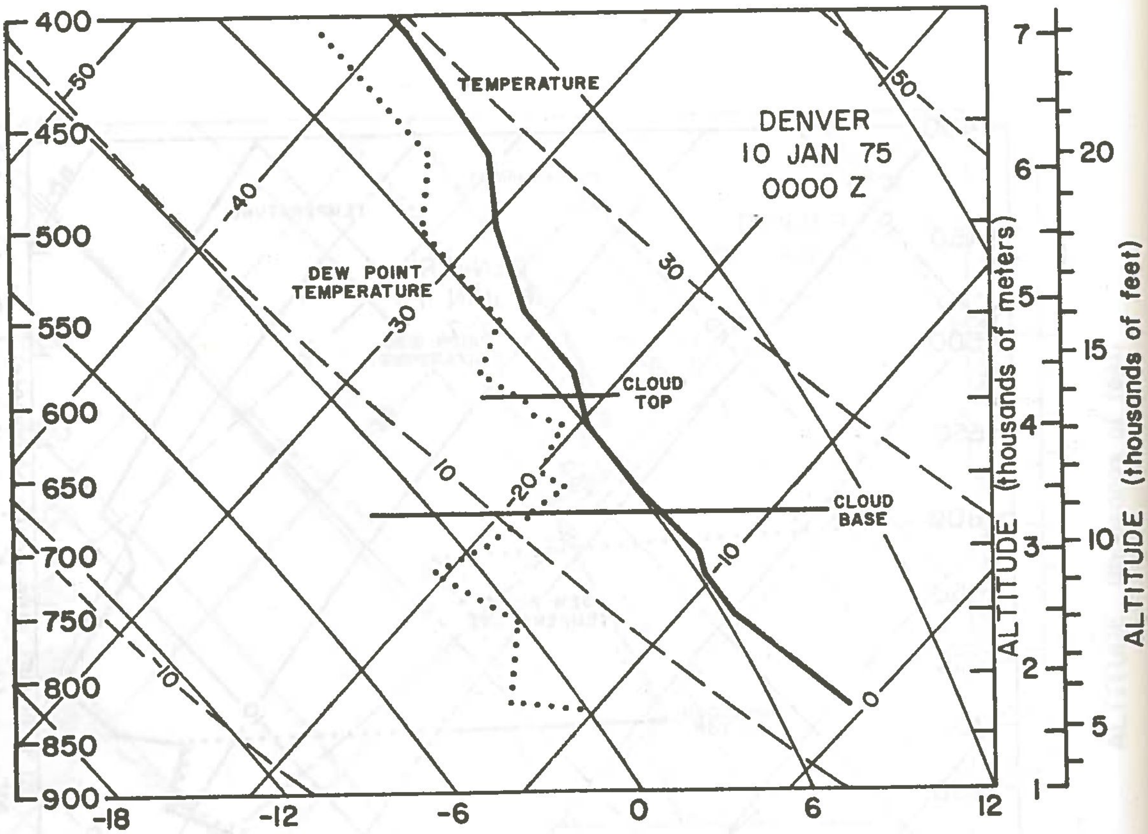


Figure 5.2d Same as Figure 5.2a

Euler-Cauchy scheme was used to replace the fourth order Runga-Kutta scheme. The simulation was terminated after the crystal had fallen through a distance equivalent to the thickness of the cloud. The results of the model are shown in figure 5.3 for a 20 cm sec^{-1} updraft. The results indicate that ice crystal or active ice nuclei concentrations between 1.0 and 10 No. ℓ^{-1} will optimize the efficiency of the cloud. The results also showed a depletion of the liquid water after 30 minutes at large ice crystal concentrations (10 No. ℓ^{-1}). As the crystal concentration was decreased the depletion became less severe until at $\sim$5 ice crystals per liter the generation of water by the updraft was balanced by the removal by the ice crystals (see figure 5.3). The model runs with a 20.0 cm sec^{-1} updraft were considered to represent those sections of the cloud where the localized topographic gradient generate such cloud updrafts.

Additional runs were made with the vertical velocity set equal to the meso-scale topographic velocity. The results are shown in figure 5.4. They indicate an ice crystal concentration of 1.0 No. ℓ^{-1} was required to balance the generation and consumption rates of water in the cloud. These runs were considered to represent the less dynamic sections of the cloud outside of the convective areas.

The meso-scale updraft for upslope clouds was estimated be equating it to the topographically induced uplift. Calculations were made of the uplift for those days which were determined to have upslope clouds present during a Climax experimental day. For this purpose the Denver radiosonde 00Z, 12Z, and 00Z soundings were used. The average low level wind was determined for each sounding by vectorially averaging the reported surface, 800 mb and 750 mb level winds. This average layer wind

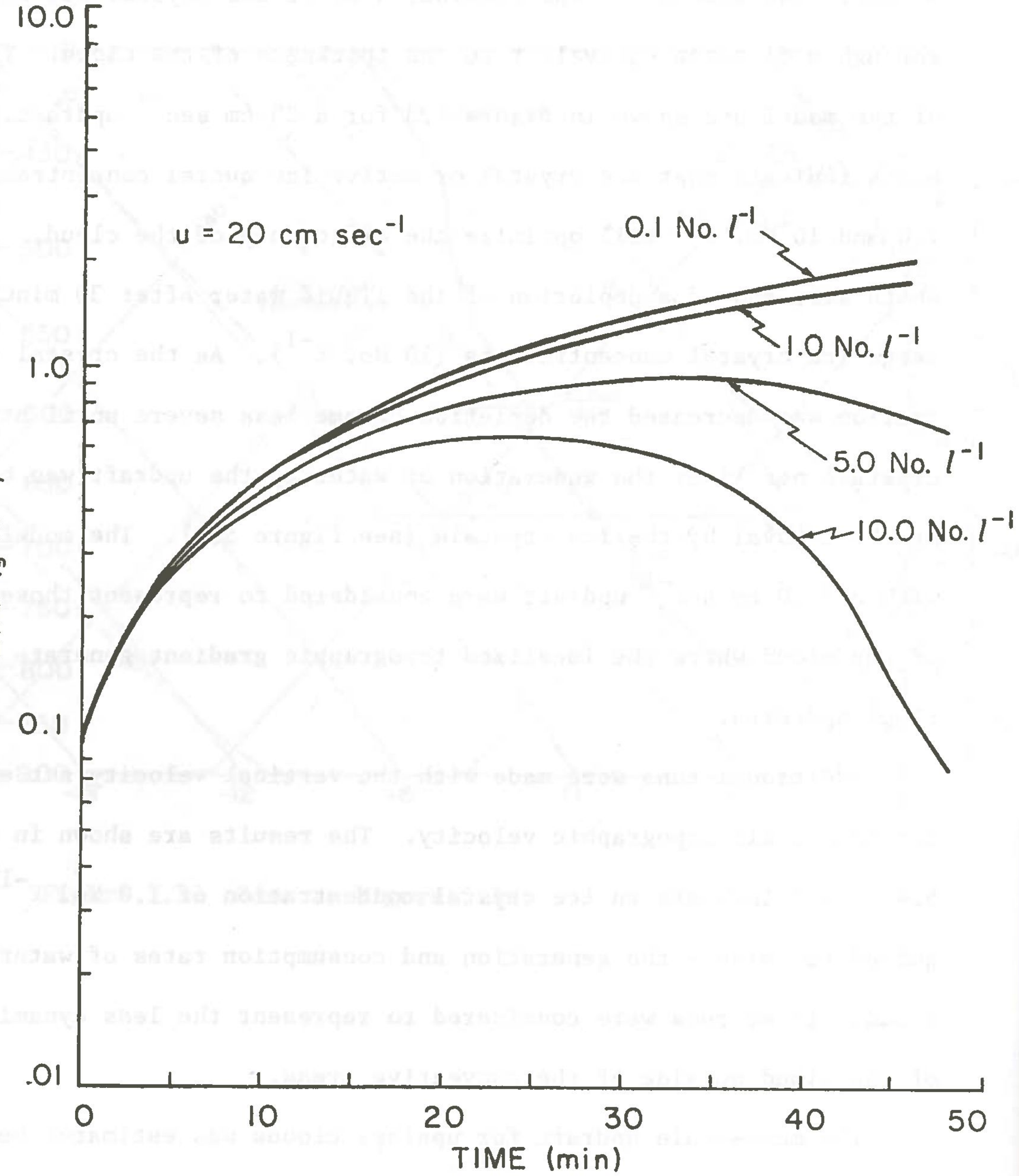


Figure 5.3. Rapid Glaciation Model results for an upslopw cloud as described by Whiteman (1973) for various ice crystal concentrations.

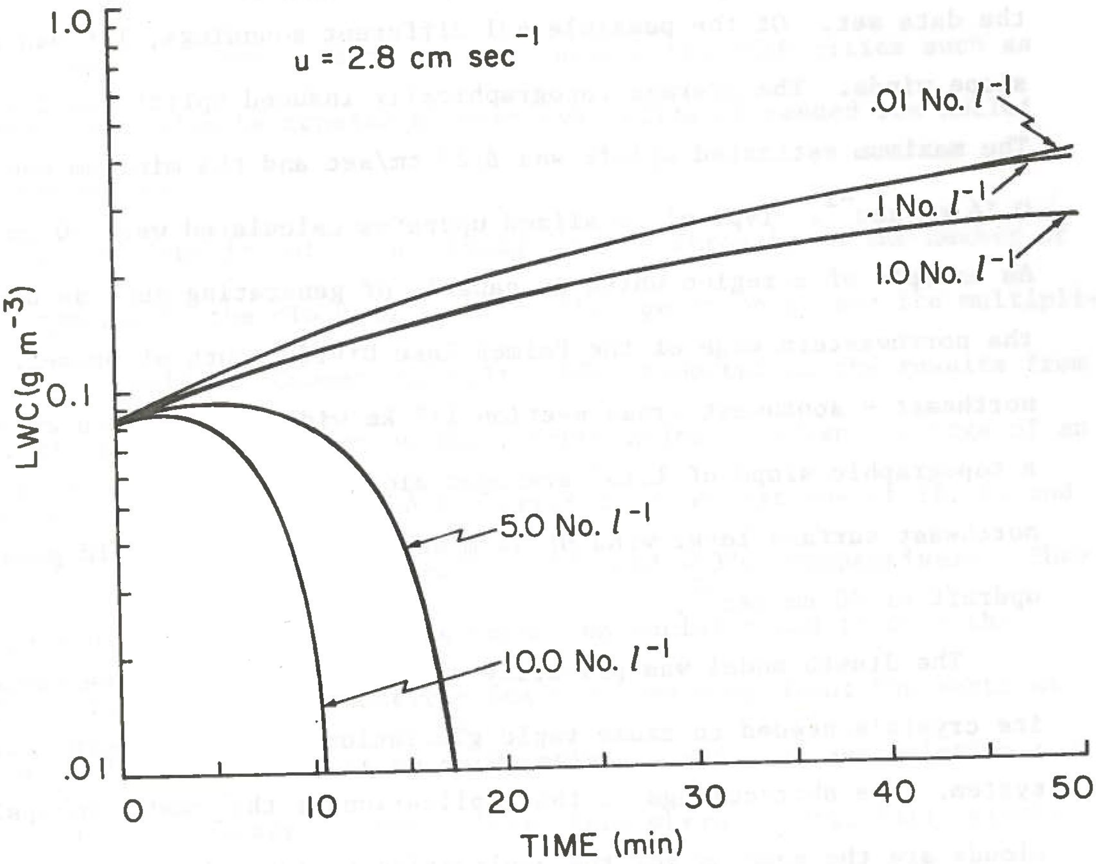


Figure 5.4. Results of Rapid Glaciation Model for various ice crystal concentrations. Initial Conditions same as figure 5.2

was then multiplied by the topographical slope. The topographical slope was estimated for each of five radials originating at Denver. Those days without upslope winds at Denver during the sounding were eliminated from the data set. Of the possible 431 different soundings, 198 had mean upslope winds. The average topographically induced uplift was 2.8 cm sec^{-1}. The maximum estimated uplift was 8.22 cm/sec and the minimum was 0.14 cm sec^{-1}. Typical localized updrafts calculated were 20 cm sec^{-1}. An example of a region which is capable of generating such an updraft is the northwestern edge of the Palmer Lake Divide south of Denver. A northeast - southwest cross section 115 km wide through this area yields a topographic slope of 1.15° averaged along a 60 km fetch. Given a northeast surface level wind of 10 m sec^{-1} this region could generate an updraft of 20 cm sec^{-1}.

The Jiusto model was primarily designed to estimate the number of ice crystals needed to cause rapid glaciation in a stratiform cloud system. The shortcomings of the application of this model to upslope clouds are the same as for the application to lake effect clouds. These limitations were outlined by Jiusto (1974). Briefly the model does not allow variations of pressure, temperature, vertical velocity or droplet concentration. These parameters do vary in the vertical as well as in the horizontal within real upslope clouds. The limitations thus imposed are not thought to seriously affect the model results, although in any attempt to predict surface precipitation rates they would represent serious problems.

The application of this model to the conditions of upslope clouds as outlined by Whiteman (loc cit) has demonstrated a clear potential for increasing the precipitation from these clouds. The naturally available ice crystal concentrations are in the range of .006 No. ℓ^{-1}, while the optimum ice crystal concentrations are between 1 and 10 No. ℓ^{-1}. Locally available ice nuclei concentrations may also be generated by inadvertent anthropogenic sources. Such sources, associated with cities such as Denver, must also be considered when evaluating nonseeded ice nuclei concentrations.

The seedability of these clouds depends strongly on the number of ice crystals in the cloud and thus on the operation of any ice multiplication mechanisms. Cooper and Vali (1976) reported on the results from aircraft measurements made during a penetration of advancing edge of an upslope cloud. They observed ice crystal concentrations of 10, 5, and 2 No. ℓ^{-1} at temperatures of -17°, -15°, and -13°C, respectively. They suggested that the ice crystals formed on nuclei mixed through the frontal surface. Their observations and reasoning about the vertical velocity in the region of the observations suggest an accumulation region within the upper reaches of the cloud where crystal fall velocities are balanced by the updraft. There the crystal concentrations increase until the crystal terminal fall velocity exceeds the updraft. Because the observations were confined to the leading edge of the upslope cloud, no general inferences can be drawn regarding the crystal concentrations and crystal-to-primary-ice nuclei ratio in the main cloud sections.

Indirect evidence concerning the efficiency of the upslope clouds was also provided by the work of Scheetz and Grant (1976). The theoretical calculations they made suggest that the upslope cloud is inefficient at the warmer cloud top temperatures. This implies that, on the whole, multiplication mechanisms may not be operative in the upslope cloud.

Proposed modes of secondary ice particle production require either graupel particles (Henmi and Grant, 1974), large water droplets with graupel particles at warm temperatures (Hallett and Mossop, 1974), or large concentrations of rimed ice crystals (Vardiman, 1974). Since the conditions most conducive to secondary ice particle production seem unlikely to exist within the upslope cloud, one may assume an ice crystal to primary ice nuclei ratio near one. With the current state of ice nuclei counters, the number of nuclei activated in a cloud can only be estimated. The actual values may differ by a factor of 10 or more from the estimated concentrations. Keeping this in mind, the number of crystals activated at the model cloud temperatures using the climatological spectra given by Chappell (1970) may be estimated by

$$N_i = 2.575 \times 10^{-4} \exp [-0.435 \Delta T].$$

These indicate .037 No. ℓ^{-1} activated at -11.4°C and .006 No. ℓ^{-1} activated at -7.2°C (temperature used in the Jiusto model). Thus one may conclude that any ice crystals or active ice nuclei added to the cloud will increase the cloud efficiency up to ~5 No. ℓ^{-1}, where the efficiency is optimized. The results of this model are significantly different from estimates made for the mountain orographic cloud by Chappell (1970). This is due to the increased importance of riming as a condensate consumption mechanism in the upslope cloud.

5.4 Influence of Urban Aerosols

As previously indicated, ice nuclei concentrations in the vicinity of Denver were observed to be higher than normal background values at low altitudes. Because such concentrations were not observed on all nonseeded flights the persistence and source of the anomaly cannot be determined. If, however, the high concentrations observed are typical, they will influence the seedability of any clouds near front range cities such as Denver. Using the same slope as Chappel's ice-nuclei-temperature equation, the concentrations of inadvertant anthropogenic ice nuclei active at typical upslope cloud top temperatures were estimated to be between .004 and .01 nuclei ℓ^{-1}.

The results of Jiusto's model suggest that these concentrations could increase the cloud efficiency for both convective-like and more stratiform regions of the upslope cloud. Additional concentrations supplied by orographic seeding operations would increase further the efficiency of the convective regions. The more stratiform regions of the cloud, on the other hand, might experience a decrease in the precipitation efficiency by rapid glaciation. Fortunately, the low level air containing these urban nuclei will be subjected to a strong cloud growth environment as the easterly winds encounter the foothill mountains. It therefore appears unlikely that any anthropogenic ice nuclei would seriously alter the seedability of large sections of the upslope cloud to such an extent as to change the sign of the precipitation alteration, that is, whether the precipitation would be increased or decreased.

5.5 Ice Crystal Transport Model

An analysis of surface ice crystal data from the Wolf Creek Pass Pilot seeding project was conducted by Vardiman (1976) on seeded and nonseeded storm systems. The analysis showed that both the ice crystal concentration and size increased for seeded vs. nonseeded storms. The average size increase was 21% and concentration increased by 325%. As the ice crystal's horizontal range could be increased, and the increased concentration could stimulate clouds which ice crystals enter downwind of the seeded cloud. Thus the ice crystal transport hypothesis merits further investigation. The validity of the transport section hypothesis was examined using a numerical microphysical model.

The microphysical model of a subliming, stable and growing ice crystal was used in conjunction with estimates of typical horizontal fields to predict the survival time and horizontal range of ice crystals leaving the orographic cloud near Climax. The subliming model, itself, is basically that of Hall and Prupacher (1976) without radiational effect, except that the subliming hexagonal plate is transformed into a prolate spheroid and finally to a sphere. Using Auer and Veal's (1970) aspect ratio relationship, Podzimek's (1968) Cd-Re relationship, and Jayaweera (1971) capacitance factor, the final set of equations used were:

$$dm/dt = 4\pi CS_i \left[\frac{L_s}{TKF_\alpha F_Q} \left(\frac{L_s m_v}{R^*T} - 1 \right) + \frac{R^*T}{e_s m_v DF_\beta F_m} \right]^{-1} \quad (5.2)$$

$$C = .5D(1-e^2)^{\frac{1}{2}} \Big/ \sin^{-1} (1-e^2)^{\frac{1}{2}} \quad (5.3)$$

$$h = 2.020\ D^{.449} \quad (5.4)$$

$$C_d = 16.5\ \mathrm{Re}^{-0.466} \quad (5.5)$$

These equations were closed as a set by using the concept of the Best number of subliming crystal calculations.

The growth equation of Mason (1971) was used in the calculation of the survival times of stable and growing ice crystals.

$$\frac{dm}{dt} = 4\pi CS_i \left(\frac{L_s}{kT} \left\{ \frac{Lm_{sv}}{R^*T} - 1 \right\} + \frac{R^*T}{Dm_v e_s} \right)^{-1} \quad (5.6)$$

The terminal fall velocity of the stable and growing ice crystals was determine from the relationship for unrimed planer crystals of Hobbs et al. (1973).

$$V = 1.65 \times 10^5 r^2 \qquad r < 0.0035 \text{ cm.} \tag{5.7}$$

$$V = 608\ r^{1.01} \qquad 0.0035 < r < 0.05 \tag{5.8}$$

$$V = 76.9\ r^{0.32} \qquad 0.05 < r \tag{5.9}$$

The results of these equations were corrected for altitude variations. The ventilation factor equation developed by Jayaweera (1971) was also used.

$$F_V = 0.11\ \{ \mathbb{R}e(1 + 2e)\}^{\frac{1}{2}} \tag{5.10}$$

The same aspect ratio and capacitance equations used in the subliming crystal section were used in this section to complete the equation set. In either case the computational scheme used to evaluate the set was the same.

The equations were solved iteratively for a 5% mass change. The crystals were allowed to fall from an initial pressure level (p_o) and height (z_o) at their terminal fall velocity and to advect horizontally with the mean wind. The crystal-dependent quantitities were adjusted after every timestep, while the pressure and temperature-dependent quantities were adjusted after the crystal fell through a 50-mb thick pressure layer. The temperature was adjusted from the initial value to a new value using a constant lapse rate atmosphere determined from the United States standard atmosphere for January at 45°N. The equation used was

$$T = T_o \left(\frac{p}{p_o}\right)^{\frac{R^*\Gamma}{gm_d}} \tag{5.11}$$

The height increment which defined the 50-mb layer thickness was also taken from the U.S. standard atmosphere. In this fashion, the particles were moved vertically while a mass change, if any, occurred.

The initial conditions for the model were initial temperature (T_o) as specified, P_o of 500 mb, and Z_o of 5100 m; and the final conditions were either the crystal mass less than or equal to 5×10^{-11}g or an altitude less than or equal to 2100 m. A constant ice saturation value was assumed at all levels. A typical sounding which the model used is given in Table 5.2.

The initial pressure and starting altitude were chosen as 500 mb and 5100 m, respectively, to simulate the level that a crystal at cloud top (460 mb) would have upon exiting the downwind cloud edge after a descent in the lee of the mountain range.

One of the limitations of the ice crystal transport model is in the terminal fall velocity section for subliming crystal calculations. The reason is that the Best number closure technique (for the velocity) is overly sensitive to changes in the dynamic viscosity. This causes an overestimation of the terminal fall velocity at lower elevations. These higher velocities are partially compensated for in the smaller crystal sizes at lower elevations. The same problem, but of a lesser magnitude, was experienced in the stable and growing crystal calculations. The fall velocity in this section was directly adjusted for altitude changes by multiplying the calculated values by:

$$\left[\rho_s/\rho_x\right]^{\frac{1}{2}} \tag{5.12}$$

where ρ_s is the air density at sea level and ρ_x is the air density at the "x" level. This adjustment was less than that attempted by Heymsfield (1972) which itself was an overestimation.

Graphical representations of the results in terms of survival time from a subliming ice crystal transport are shown if figures 5.5, 5.6 and 5.7. The ordinant on these graphs (survival time) may be converted to

Table 5.2 Typical Sounding for Ice Crystal Transport Model

T_o=-20°C   Saturation Ratio= 0.9

Pressure (mb.)	Temperature (°C)	Relative Humidity (%)
500	-20.0	74
550	-15.7	77
600	-11.7	80
650	-8.0	83
700	-4.6	86

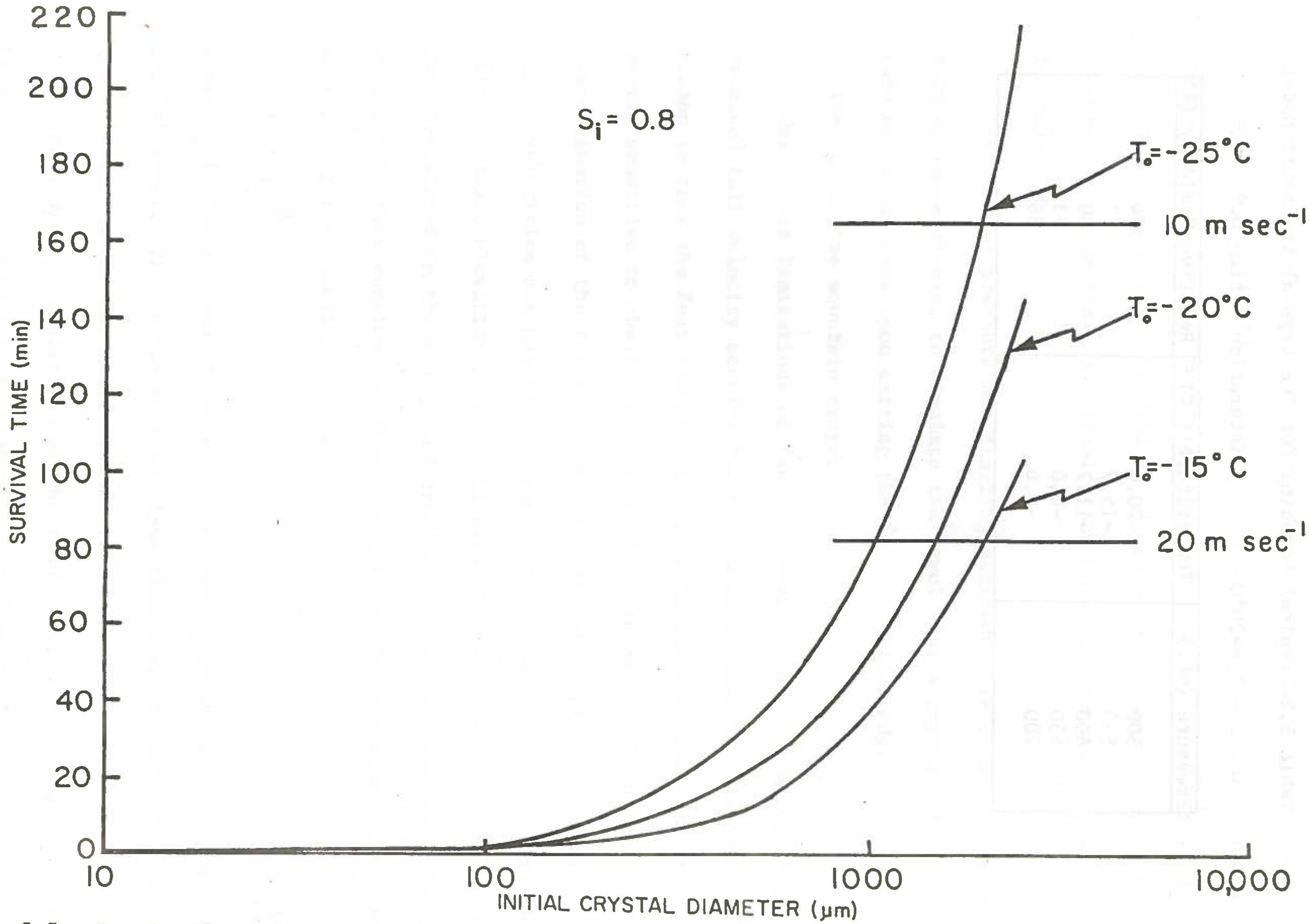


Figure 5.5. Results from the ice crystal transport model for subliming conditions. Survival times requires for crystals to reach the upslope cloud edge with various winds are shown.

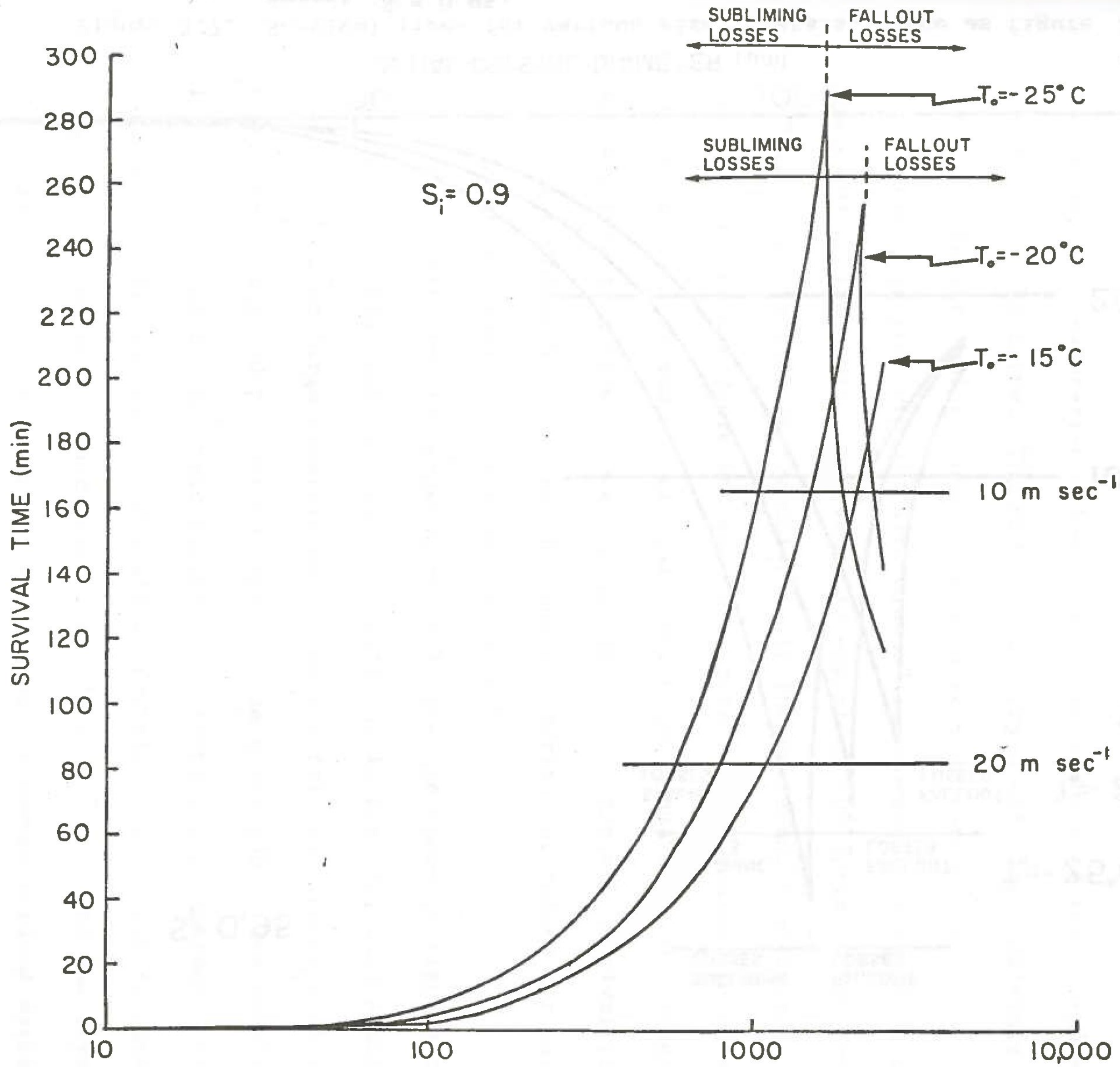


Figure 5.6. Survival times for various size crystals. Same as figure 5.5 except $S_i = 0.90$

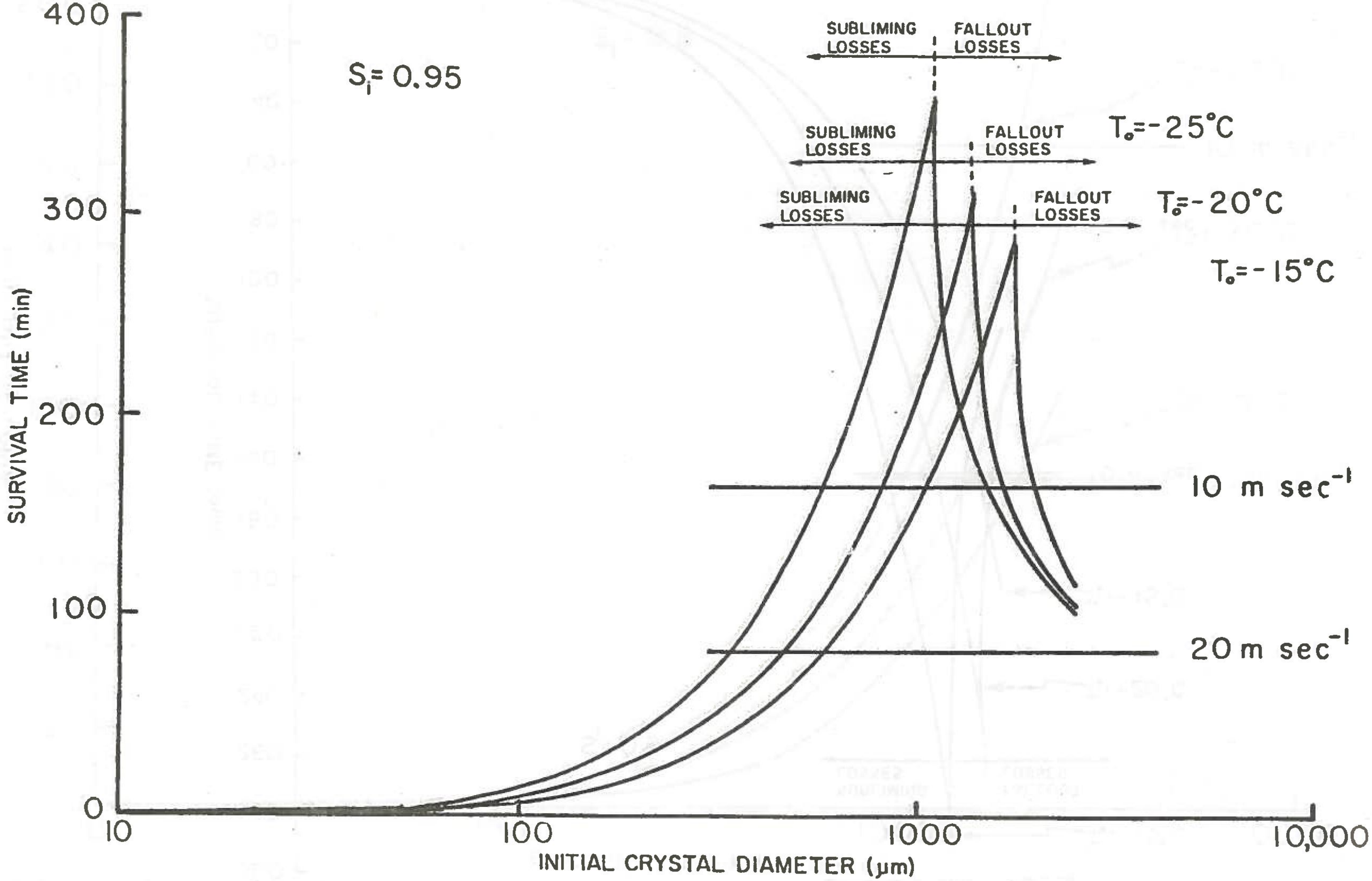


Figure 5.7. Survival times for various size crystals. Same as figure 5.5 except S_i = 0.95

horizontal range by multiplication by typical horizontal wind speeds. The graphs show the survival time of a spectrum of ice crystals (similar to those observed in orographic storms) for three initial temperatures and several ice saturation values. A common feature of these graphs is the shape of the curve. The crystals of very small size completely sublimed in the air, while those of very large size rapidly fell out. In this manner, an ice crystal "size window" was formed, within which optimum survival times were achieved. As expected, the optimum size shifted to small ice crystals as the moisture in the environment increased. This was a result of the decreased mass loss rate and the smaller terminal fall velocities of smaller crystals, which thus remained aloft longer and sublimed at a slower rate. A summary of the maximum survival times, the corresponding ice crystal size and the horizontal ranges for various environmental conditions is given in Table 5.3.

The results for the growing crystal case are shown in figures 5.8 and 5.9. In this case gravitational settling is the only loss mechanism. Aside from large crystals which rapidly fall out the crystal life times are strongly dependent on crystal size above 100 μm and weakly dependent on the initial temperature. The temperature dependence is such that colder initial temperatures allow crystals of all sizes to survive longer. In a moderate upper level wind (20 m sec^{-1}) all of the crystals will survive in the long range transport to the downwind cloud systems. In weaker wind fields (10 m sec^{-1}), or with higher ice supersaturations, the gravitational losses become more severe. A summary of the survival times and horizontal ranges are given in Table 5.4.

The survival time results for stable crystals are shown in figure 5.10. A comparison of the survival times for a spectrum of crystal sizes

Table 5.3 Results from the Ice Crystal Transport Model

Initial Temperature (°C)	Maximum Survival Time (min)		Optimum Initial Crystal Diameter (μm)		Maximum Horizontal Range (u=10 m sec^{-1}) (km.)		Maximum Horizontal Range (u=20 m sec^{-1}) (km.)	
	S_i=.9	S_i=.8	S_i=.9	S_i=.8	S_i=.9	S_i=.8	S_i=.9	S_i=.8
-25	289	>217*	1700	>2500	173	130	347	260
-20	254	>146*	2200	>2500	130	88	260	175
-15	>206*	>103*	>2500	>2500	124	62	247	124

*Values shown are for the largest crystal size investigated (2500 μm)

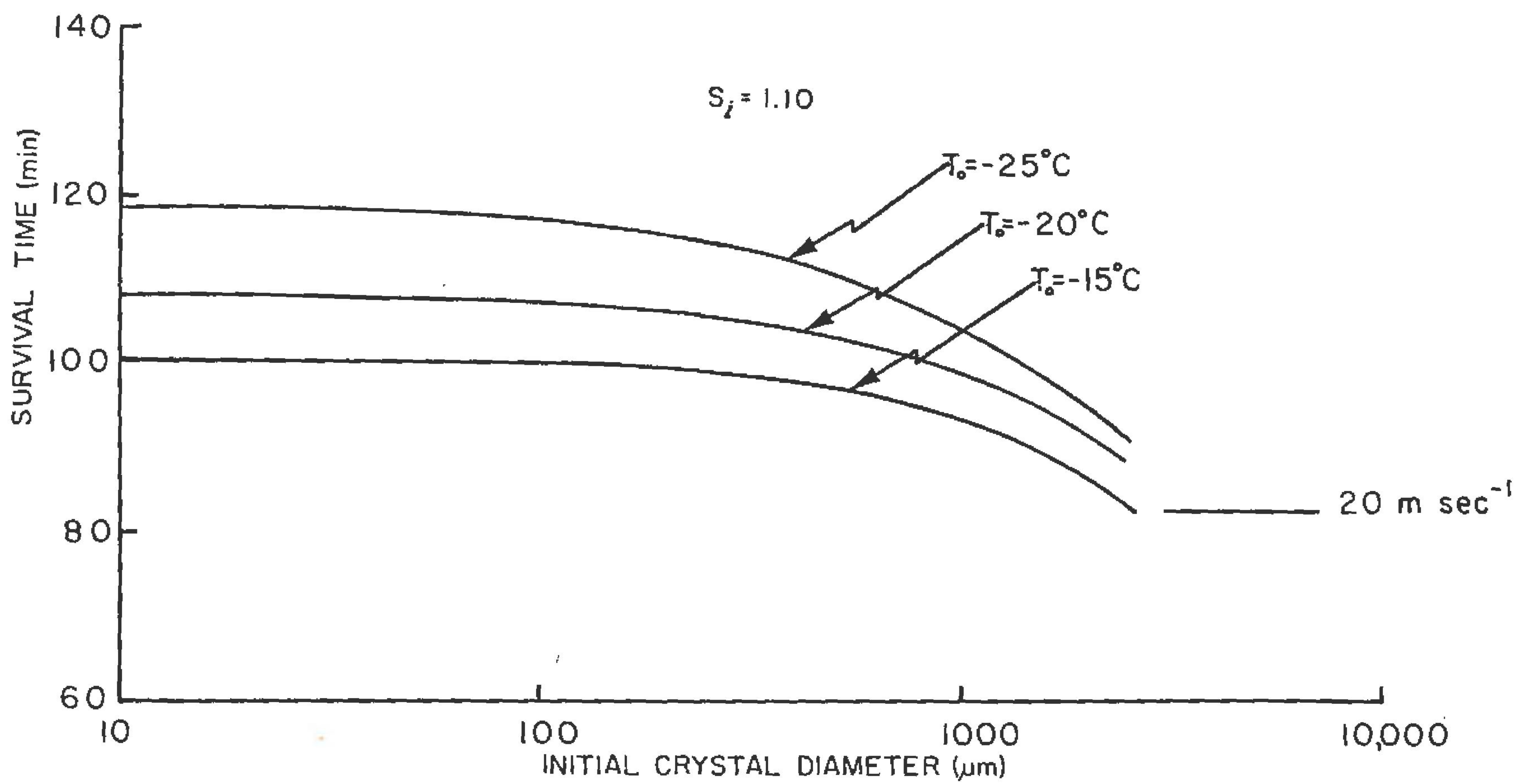


Figure 5.8. Results from Ice Crystal Transport Model for growing crystals where S_i = 1.10. The survival times required for the crystals to reach the downwind clouds are shown for two wind speeds.

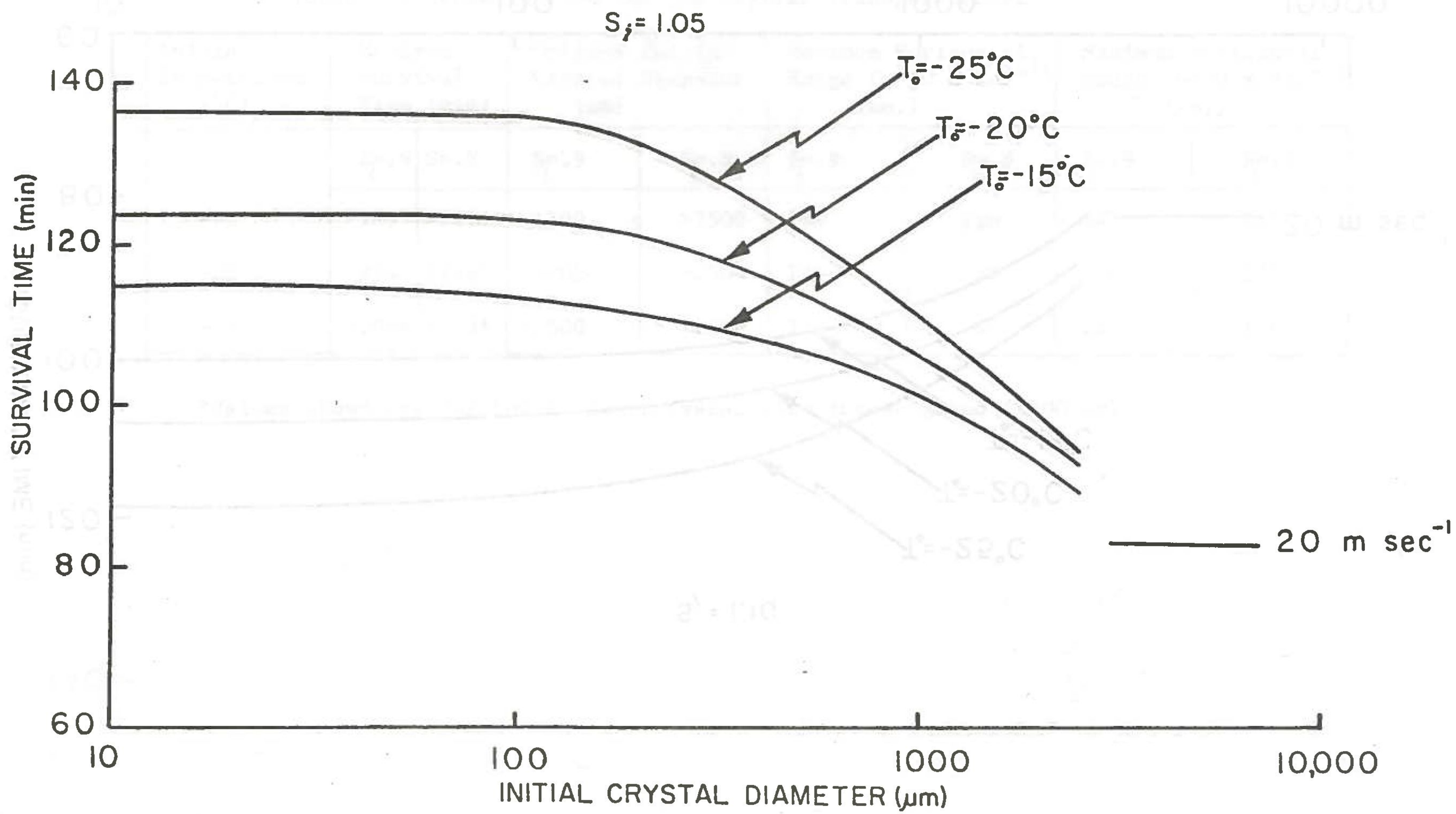


Figure 5.9. Same as Figure 5.8 except S_i=1.05.

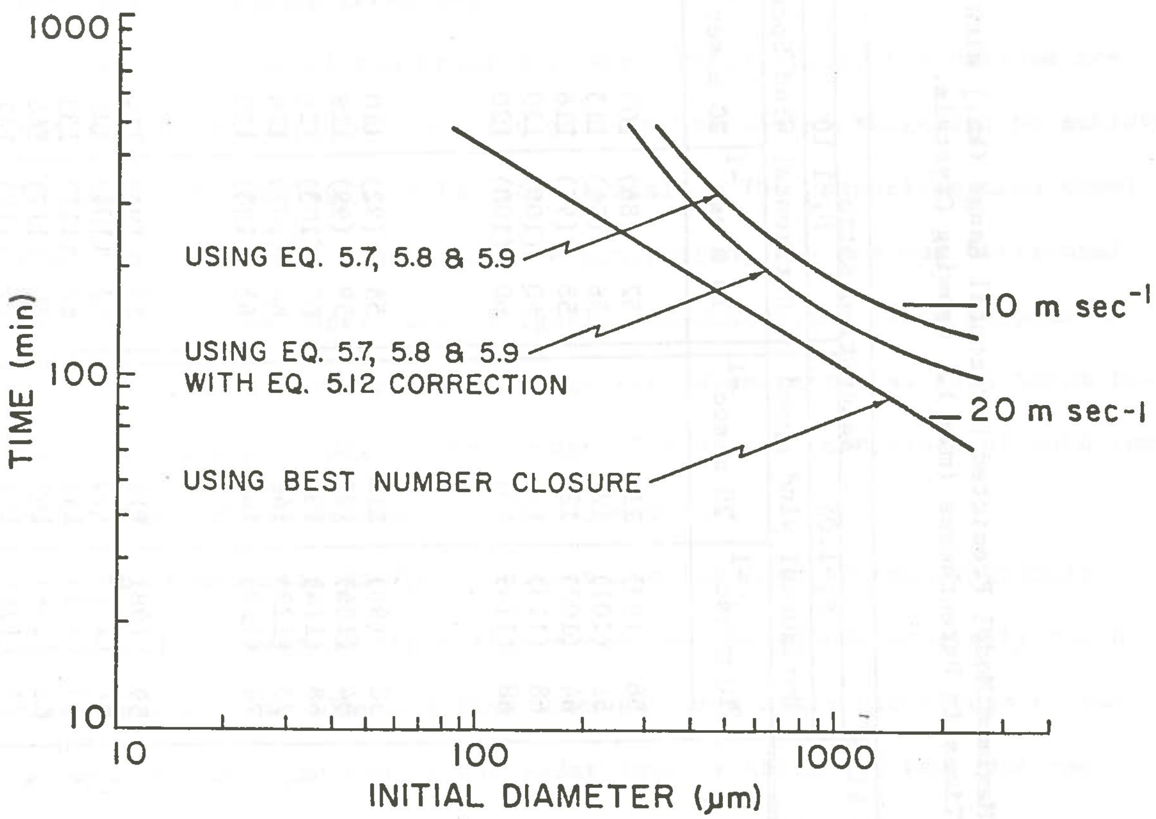


Figure 5.10. Stable crystal survival time.

Table 5.4. Maximum Model Predicted Horizontal Range (km.) with Survival Times in Parentheses (min.). Growing Crystals.

Initial Crystal Size (μm)	Saturation Ratio			
	S_i=1.05		S_i=1.10	
	Horizontal Wind Speed		Horizontal Wind Speed	
	10 m sec^{-1}	20 m sec^{-1}	10 m sec^{-1}	20 m sec^{-1}
T_o= -15°C				
2000	56 (93)	112	52 (86)	103
1000	61 (101)	121	56 (94)	113
500	64 (107)	128	58 (97)	116
100	68 (113)	136	60 (100)	120
50	68 (114)	137	60 (100)	120
T_o= -20°C				
2000	58 (96)	115	55 (92)	110
1000	64 (106)	127	59 (99)	119
500	68 (114)	137	62 (103)	124
100	73 (122)	146	64 (107)	128
50	74 (123)	148	65 (108)	130
T_o= -25°C				
2000	59 (98)	118	57 (95)	114
1000	67 (111)	133	62 (104)	125
500	73 (122)	146	67 (111)	133
100	82 (136)	163	70 (117)	140
50	82 (136)	163	71 (118)	142

* All values are rounded off to the nearest whole interger.

utilizing various fall velocity equations is shown in this figure. The formulation using the Best number closure technique consistently showed the lowest survival times. The crystals whose fall velocities were adjusted using equation 5.12 were shown to have survival times between those without altitude dependent fall velocities and those using the Best number closure technique.

A comparison of the transport model calculations for various ice saturation ratios shows that the maximum horizontal range can be achieved by small non-growing (stable) ice crystals. The comparison also shows that for conditions other than ice saturation, the maximum horizontal transport occurs under cold, slightly undersaturated (with respect to ice) conditions. For small crystals with diameters less than 500μm the maximum transport range occurs under slow growth conditions of cold temperatures and ice saturation ratios near one.

The horizontal distance between the lee edge of the orographic cloud and the edge of the region where upslope clouds generally reach was about 100 km. The distance from the orographic cloud edge to the genesis areas suggested by the radar data is about 240 km. One can therefore state that under certain meteorological conditions, ice crystals with a west wind will reach the upslope cloud over the eastern plains region. It should be noted, however, that this approach does not include any vertical velocity fields (synoptic, mesoscale or orographic), nor any associated change in the ice saturation field. Depending on the sign of the vertical velocity, the maximum horizontal range could be enhanced or decreased. Based on the work of Vardiman and Hartzel (1976) it was estimated that approximately 0.5 to 50.0 crystals per liter are within the size band of crystals which could reach the upslope cloud.

An analysis of the Denver 550 mb level ice saturation ratio values for Climax experimental days with upslope clouds present was performed to estimate the fraction of days which would allow an effective transport of ice crystals. The 550 mb level was chosen as being representative of the mean transporting layer between the downwind edge of the orographic cloud (500 mb, 5437 m) and the upslope cloud tops (3900 m ~615 mb for the main cloud and 4685 m ~555 mb for convective radar tops). The results of the analysis are shown in Table 5.5.

These results indicate ice crystals could be transported some distance downwind for about 69% of the days in the data set. It should be remembered, however, that the Denver soundings may not be representative of the meso-scale moisture conditions over the mountainous terrain to the west.

TABLE 5.5 550 mb. Ice Saturation Frequencies
for Climax Experimental Days
When Upslope Clouds were Present

ICE SATURATION	$S_i > 0\%$	$0 > S_i > -10\%$	$-10 > S_i > -20\%$	$-20\% > S_i$
Frequency	43.5	17.9	8.2	30.4
Cumulative Frequency	43.5	61.4	69.6	100.0

CHAPTER VI

CLIMATOLOGICAL STUDIES

In order to explore the mode of interaction between the material transported downwind from Climax to the Front Range and eastern plains, and any cloud systems which could be present, we must enumerate the type, frequency and characteristics of the downwind cloud systems. This type of information was obtained through a series of climatological-historical studies. The studies were based on three general types of data. They were data from previous studies, from area-wide precipitation data, and from a combination of area-wide surface observations and radiosonde data. The precipitation data were used to identify the general cloud type responsible for the majority of wintertime precipitation observed on the eastern plains and near foothill regions of Colorado. The data from previous studies were used to calculate the frequency of occurence and to identify as many cloud characteristics as possible. The data from the surface observations and radiosondes were used to fill in some of the gaps in the previous studies. The additional studies were also needed to identify the general synoptic conditions under which the clouds downwind of Climax formed.

6.1 Downwind Cloud Systems

A climatological study of the precipitation characteristics was used to determine which cloud systems were of most interest in the downwind area over the eastern plains of Colorado. Hourly precipitation data from the NOAA precipitation network in eastern Colorado was examined for a period of 10 to 16 years. The data were stratified by time of year, average station precipitation duration, the number of stations recording precipitation and the percentage of stations with a maximum precipitation rate greater than or equal to 2.54 mm $hr.^{-1}$.

The results of this study have been presented by Henz et al. (1976) and will be only summarized here. The upslope clouds were found to provide 80% of the wintertime precipitation and 22% of the annual precipitation received by the foothill and eastern plains region. The average episode duration per station was approximately seven hours. The average station precipitation intensity was 0.74 mm hr^{-1} and the average precipitation per station was 4.62 mm. These estimates do not include the contribution of upslope sections of other general classifications, such as stratiform clouds in advance or to the rear of active frontal systems. If one includes these components the upslope cloud supplies ~90% of the wintertime precipitation and 34% of the annual precipitation. It was thus decided to concentrate on upslope cloud systems as the type most likely to be affected by any extra-area precipitation alteration.

6.2 Climatological Characteristics of Upslope Clouds

Two approaches were used to determine the climatological characteristics of upslope cloud. The first approach consisted of a literature search for information. The second approach was to use historical data to identify and quantify the characteristics of upslope clouds. In particular, the upslope clouds which occurred simultaneously with seeding events at Climax were studied.

6.2.1 Previously Determined Upslope Cloud Characteristics

Whiteman (1973) used radiosonde data for Denver for a period of ten years (January 1961 through December 1970) to identify the wintertime cloud characteristics. The criteria used by Whiteman (loc. cit.) to define the presence and characteristics of seedable upslope clouds were based on radiosonde data. A moist layer (relative humidity greater than or equal to 85%) must be within one kilometer of the surface and be at least one kilometer thick. A distinct moist layer top must be observed and have a temperature between -5 and -15°C. Allowances were made for certain borderline cases. A sounding was classified as an upslope event if it met the above criteria. The frequency of occurrence of upslope cloud for the Denver area which emerged from this study are given in Table 6.1.

Additional charcteristics which were compiled for the Central Plains Region (Colorado, Nebraska, and Kansas) are given in Table 6.2.

Scheetz and Grant (1976) have investigated the seedability of upslope storms in eastern Colorado. They used cloud top temperature estimates derived from IR satellite data (NOAA-2), surface precipitation data, and theoretical calculations of condensate rate for twelve upslope storm days (14 events) during the period from October 1973 to April 1974. Their results showed that 46% of the cloud top temperature observations made on upslope days fell between 250°K and 265°K. This is the temperature range previously described by Grant and Elliott (1974) as the "seeding window", where cloud seeding could enhance precipitation. Scheetz and Grant (loc. cit.) also observed that a fraction (varying from 11% to 95%) of the cloud tops on all twelve days had temperatures within the "seeding window."

A precipitation analysis performed showed that the seven coldest cases averaged more than three times the precipitation of the five warmest cases. These results are in general agreement with the results of Grant and Elliott (loc. cit.). An examination of the distribution of the cloud

Table 6.1 Climatological Occurrence of Upslope Clouds Based on Nov.- April Denver Data (Whiteman, 1973)

Month	Avg. Number of Events per Month	% of Annual Wintertime Occurrences of Upslope Clouds
Jan.	2.0	16.4
Feb.	2.6	21.3
Mar.	2.5	20.5
Apr.	1.2	9.8
Nov.	1.6	13.1
Dec	2.3	18.9
Winter Total	12.2	100.0

Table 6.2 Physical Characteristics of Upslope Clouds

Cloud Base Height msl	1882. m
Cloud Base Temperature	-3.0°C
Cloud Top Height msl	3905. m
Cloud Top Temperature	-11.4°C
East Wind Component at Cloud Base	1.6 m/sec

top temperatures indicated that a maximum of 36% of the observations would have been classified as seedable under the Whiteman (loc. cit.) seedability definition. The conclusion drawn from this work is that a degree of spacial variability of cloud top temperature (and probably, seedability) exists within the upslope cloud, and that the frequency of occurrence of truly seedable upslope clouds reported by Whiteman (loc. cit.) may be low.

6.2.2 Upslope Cloud Characteristics on Climax Experimental Days

An objective scheme was developed to identify the days on which upslope clouds were present. The purpose of identifying these days was primarily to gain information concerning the frequency of occurrence of such clouds on days which were experimental units within the Climax seeding project. A secondary purpose was to describe the conditions which existed on those days, such as upslope cloud vertical velocity, duration of cloud cover, and seasonal variations of the frequency of occurrence, as well as to provide an upslope cloud day list for other studies. The results of these studies would allow an analysis of whether or not the conditions were proper for any mechanisms investigated here to cause a significant precipitation alteration.

Because the number of experimental days in a given month varied due to funding, occurrence of suitable events, contaminating influences, and avalanche hazards, the frequency of occurrence results were normalized to an optimal year. The initial data set was the 688 day sample used by Janssen et al. (loc. cit.) in their *post hoc* statistical analysis. This data set was examined to identify upslope days. The approach was to use surface observations at three-hour intervals and Denver radiosonde data to determine the presence or absence of an upslope cloud when an experimental day was declared at Climax.

In order to identify the upslope cloud days a series of criteria were established using a system of primary and secondary supporting surface observation stations as shown in figure 6.1. The identification of an upslope cloud was based on certain wind direction, cloud cover, duration and moist layer requirements. The criteria were formulated to objectively identify those days of the Climax experimental data set during which a mesoscale or synoptic scale motion towards the Front Range Mountains was taking place, and which resulted in substantial amounts of cloud cover being formed for a substantial period of time. The specifics of the classification scheme are given in Appendix D.

Briefly, the surface requirements were that a specific group of three or more stations had to report a cloud cover of 60% or greater for two consecutive time periods (each three hours) and that the surface wind at these stations had to have an easterly component during the same time period. The radiosonde requirements were that a moist layer (R.H.$\geq$ 68%) had to have its base at or below 650 mb (3500 m msl), be at least 100 mb thick and be observed during at least one of the three soundings (00Z on day, 12Z on day, and 00Z on day +1).

The rationale behind the cloud cover requirements was that if three grouped stations reported a sky cover of 60% or greater a relatively large cloud system had organized. The wind requirements were designed to insure a fairly wide areal extent over which the winds were directed towards the primary uplift areas (i.e., Front Range Mountains). The radiosonde relative humidity requirement of RH greater than or equal to 68% is approximately equal to a 5° dew point depression at -10°C. The dew point depression of 5°C is the point at which there is a 50% probability of a cloud base being in the vicinity of the radiosonde (United States Air Force, 1969). This criterion was chosen in an effort to detect a cloud at some distance from the radiosonde. The minimum height criterion was chosen to differentiate between high cirrus or stratocirrus layers and a true low level upslope cloud. The height criterion does not differentiate between true upslope clouds and alto-cumulus decks. In view of the time between sounding and the spacial and temporal variability of the cloud bases, it was felt that the 650 mb level was a reasonable cutoff level for the possibility of a cloud base thickening and lowering during the period between radiosonde ascents. Together, these requirements would insure that a relatively large upslope cloud had organized and that a potential for precipitation was present.

The duration of the upslope cloud cover was determined using the average time a single station reports cloud cover greater than or equal to 60% and easterly winds during the give 24-hour period identified as an upslope condition.

The results of the upslope cloud climatology for Climax experimental days are given in Table 6.3. The observations were recorded from the North American Surface Chart series published by NOAA.

The table shows a maximum frequency of occurrences during the month of March, with February having the next highest frequency. The total number of days during which an upslope cloud was present and an experimental day would be declared was 23.2 days/winter season (total sample = 187 days). From surface observations, the average station duration of the upslope cloud was estimated to be 12.3 hours with a $\pm$ 1-1/2 hour uncertainty. Only nine days had a cloud duration less than or equal to

Figure 6.1. Surface Observation Station Sets

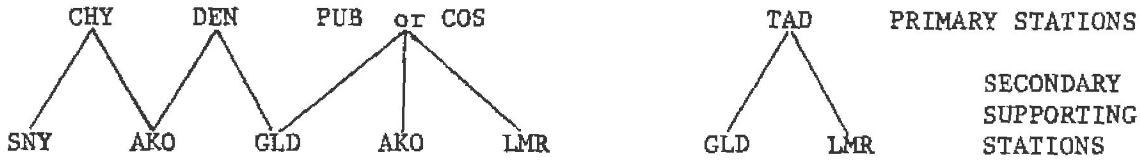


Table 6.3 Frequency of Occurrence of Upslope Clouds on Climax Experimental Days (1960-1970)

Month	Average number of Events per Month	% of Annual
Jan.	4.1	17.7
Feb.	4.6	19.8
Mar.	5.2	22.2
Apr.	3.7	16.0
Nov.	3.7	15.7
Dec.	2.0	8.6

six hours. The observed cloud duration is very reasonable when one considers the findings of Henz et al. (loc. cit.) concerning the average station duration of precipitation during upslope storms (seven hours). For the cloud to form, initiate precipitation, and then dissipate the average cloud duration would allow a period of approximately three hours before and after the precipitation event. The three-hour period is also often considered the characteristic time of the atmosphere.

The question of whether the convective-like cloud elements described in section 4.3 extend above the main upslope cloud deck was addressed by examining a set of historical Denver radiosonde soundings. If such elements do extend above the main cloud, they could act to aid in the interaction processes between the mountain orographic and upslope clouds. Soundings from a group of 128 non-treated upslope cloud days from the Climax experimental day data set were examined. The static stability

$$E_v = \frac{g}{T}\left(\Gamma_d + \frac{\partial T}{\partial z}\right) \qquad (6.1)$$

was calculated from 50 mb interval data for the layer between the cloud top and the next higher pressure level (first layer) and for the layer between the first and second pressure levels above cloud top (second layer). Approximately 25% of the soundings had an extremely stable first layer ($E_v \geq 5\text{x}10^{-4}$). The bulk of the remaining soundings (73% of the total number) had moderate stabilities ($5\text{x}10^{-5} \leq E_v \leq 5\text{x}10^{-4}$). For the second layer the percentage of extremely stable soundings decreased to about 6%. The remaining soundings fell into the moderate stability class.

This coarse 50 mb. resolution data study was supplemented by an examination of 23 soundings representing 20 upslope events from the

1965 to 1976 period. The soundings incorporated both significant and standard level data from the Denver radiosonde. Approximately 70% of the soundings were observed to have a boundary layer cold air intrusion, within which the upslope cloude had its roots. The inversions which formed the upper boundary of the cold air were typically 2° to 16°C. All soundings but one showed the upslope cloud to be capped by very stable layers (i.e., inversion, isothermal, absolutely stable, saturated neutral). This indicates that true convection originating within the main upslope cloud will quickly be suppressed as the cloud top is approached and penetrated. However, in approximately 40% of the soundings analysed, moist layers, with dew point depressions of 5°C or less, continued above the boundary layer inversion. Two meso-scale phenemona which could cause such a moistening of the upper layers are forced air-mass or topographic lifting and migrating mesoscale convergence fields associated with mid-tropospheric waves. These phenomena could give rise to localized elevations in the cloud top which would assist the interaction between the mountain orographic and upslope cloud systems.

The conclusion reached from the examination is that conditions favoring deep convection through the inversion at the top of the upslope flow do not exist frequently. On the other hand, moderate localized pertubations in the upslope cloud probably do occur frequently. The analysis also supports the results of the "ID" cumulus model experiments in that very little convective instability was shown to exist. This implies that the mode of seeding is more likely to be static as opposed to dynamic.

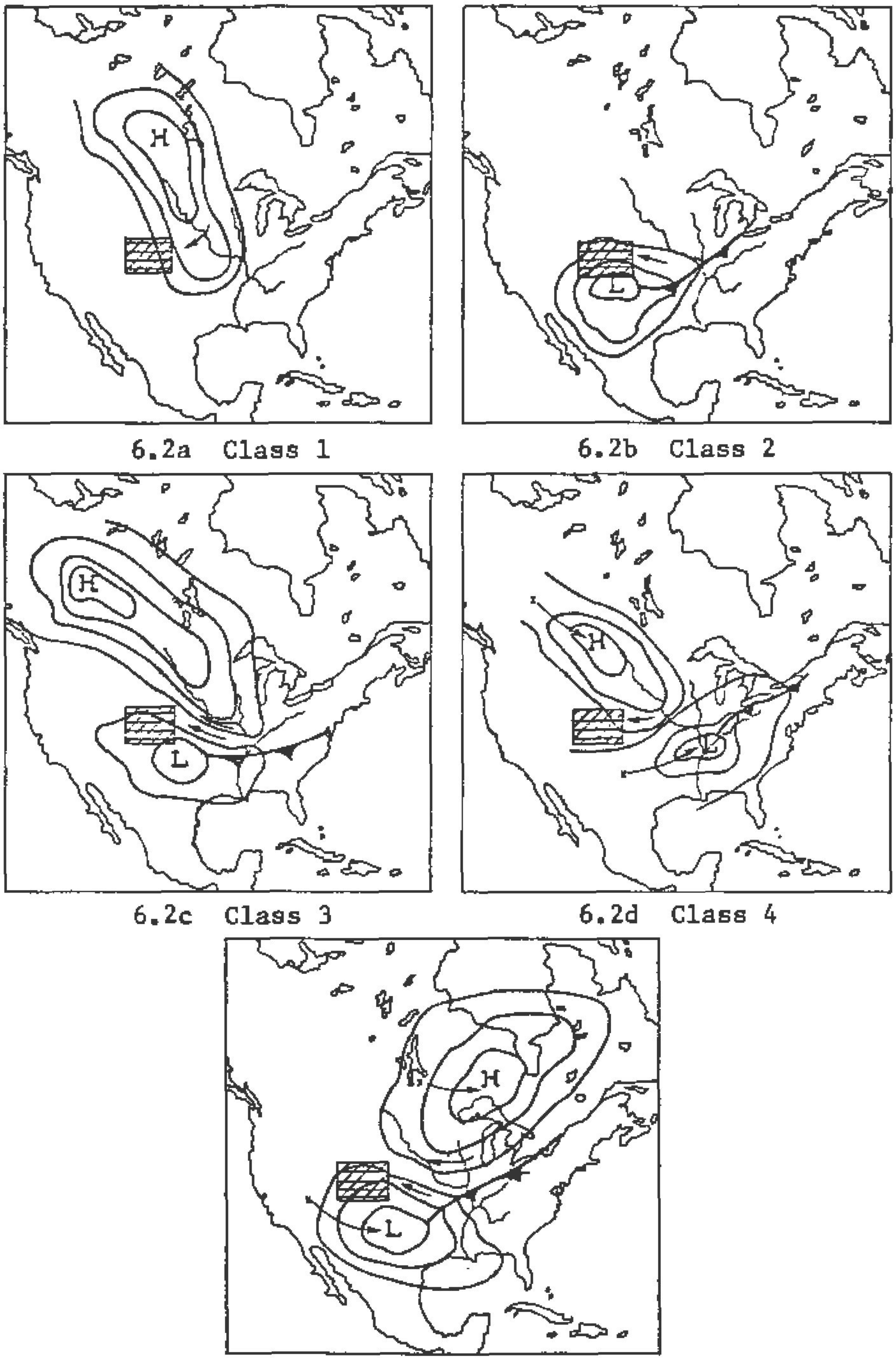
6.2.3 Synoptic Upslope Cloud Study

The purpose of the synoptic upslope cloud climatology was to identify the patterns of synoptic systems which were responsible for the presence of the upslope cloud and thereby infer some general cloud characteristics. The data set identified as having upslope clouds in the previous section provided the day list from which the synoptic climatology was prepared. Using surface maps, the investigation was made into the synoptic situation associated with the occurrence of upslope clouds over the eastern plains of Colorado.

A total of six classes were established to categorize the major surface features controlling the upslope and these patterns are illustrated in figure 6.2. These classes were:

1. A high pressure system centered north of Colorado (6.2a);
2. A low pressure system centered south or within the southern sections of Colorado (6.2b);
3. A combination of class 1 and 2 in equal proportions (6.2c);
4. A transition from a low pressure to a high pressure system controlling the upslope during the 24-hour period (6.2d);
5. A transition from a high pressure to a low pressure system controlling the upslope during the 24-hour period (6.2e); and
6. Another class, consisting of an unspecified combination of high and low pressure systems and locations.

The results of this classification are shown in Table 6.4. These results indicate that the predominant pattern causing upslope clouds to form over the eastern foothills and plains of Colorado on Climax experimental days was a high pressure aystem centered to the north of Colorado (class 1). The cold air associated with the system was frequently



6.2a Class 1 6.2b Class 2 6.2c Class 3 6.2d Class 4 6.2e Class 5

Figure 6.2 Synoptic weather classes associated with upslope cloud formation.

Table 6.4 Frequency of Upslope Clouds on Climax Experimental Days within Each Synoptic Class (186 days)

Synoptic Class	Frequency in % of Total Events
1	39.8
2	14.0
3	10.8
4	18.3
5	8.1
6	9.1
Total	100.0

observed to slide southward along the eastern slope of the Rocky Mountains causing upslope clouds. Within the cold air which moves up to the topographic gradient, a stable cloud usually forms. The moisture source for these clouds was the Gulf of Mexico. The moisture was usually transported northward to the central United States where the flow around the high pressure would carry it westward towards the primary topographic lifting areas. The clouds thus formed were stable because of the warm air aloft and the cool air at the surface. This was often exhibited as an inversion present at the cloud top.

The next most frequent pattern was a transition from a low pressure system controlling the upslope to a high pressure system. A frequent series of events observed in this case was a low pressure center tracked eastward over southern Colorado or northern New Mexico, which brought Gulf moisture into the region and initiated the upslope. As it moved away from the foothills the "wrap-around" flow would aid a high pressure system moving southward to enter the eastern plains quickly and continue the forcing of the upslope cloud. In this case any unstable regions within the upslope cloud caused by the low pressure system would be suppressed and replaced by more stable stratiform clouds due to the increasing subsidence as the high pressure system moved in.

The low pressure system centered over southern Colorado or northern New Mexico was the third most frequent synoptic pattern. On the days within this class, the upslope was forced by a low pressure system to the south. The clouds occurring during these events would be supplied with moisture by the forcing pressure system itself. Also the topographically induced vertical motion field would be superimposed on top of the synoptic scale vertical motion fields. These clouds could be expected to extend through a greater depth of the atmosphere and thus be more efficient on the whole than the thinner clouds of class 1.

The fourth most frequent category, class 3, consisted of those days when the upslope clouds were forced by both a high pressure system to the north and a low pressure system to the south. The clouds occurring on this type of day would have a complex structure which would vary spacially depending on the location and strength of the subsidence and ascending motion fields.

Class 6, "other" pressure system combinations, was the next most frequent type. Here, as in class 3, the cloud structure would be complex and not have general characteristics.

The final and least frequently observed category was class 5, the transition from a high pressure system controlling the upslope to a low pressure system. The cloud structure would start off as a stable stratiform type and gradually convert to a more unstable stratocumulus cloud type as the cold advection aloft and the warm advection at the surface set in. This type of system is potentially the most efficient. Because over 90% of the days investigated could be classified into a specific controlling synoptic pattern class it was felt the classification scheme was adequate.

In order to calculate the fraction of annual wintertime upslope storms included in the Climax experimental day set, the climatological precipitation amounts were compared to the observed precipitation amounts. The climatological precipitation amounts were determined by multiplying the fraction of the annual precipitation supplied by upslope storms given by Henz et al. (loc. cit.) by the annual precipitation for the

Denver area given by Smith and Schulz (1962). This also allowed the importance of each synoptic class in precipitation production to be assessed.

Precipitation total (6 pm to 6 pm) for a single station within the upslope storm for 63 nonseeded and non-contaminated experimental days were used. Non-contaminated days were required to be both preceded and followed by a nonseeded or non-experimental day. The amount of the precipitation from each synoptic class was established by multiplying the average daily precipitation by the annual frequency of occurrence of days within that class. The results indicate that class 1 was by far the largest producer of precipitation. It was followed by classes 2, 4, 5, 3, and 6 in order of decreasing annual winter time upslope precipitation produced. The total wintertime upslope precipitation estimated by the above procedure was about 52 mm. This corresponds to a climatological estimate of about 63 mm. The difference of about 17.5% is easily accounted for by the fact that the upslope data set used represented only a fraction of the total upslope data set, and because only a single station precipitation estimator was used.

CHAPTER VII

DESCRIPTION OF RESULTS

Any single process outlined could be active during the complete life of the storm or during a portion of it with other or no process active during other segnments. The processes outlined above have been interpreted as downwind precipitation enhancement mechanisms. A question remaining is, could a reasonable conceptual model be outlined which would suggest precipitation decreases downwind? The most probable manner in a Class I or II mechanism type in which a precipitation decrease could occur, would be through an overseeding process. During a clear transport process, ice nuclei concentrations of several hundred per liter could be transported to the downwind cloud. The actual fraction of these transported nuclei which would be involved in the initiation of precipitation processes would depend strongly on the cloud top temperature. Physical observations of massive overseeding of some types of storms have suggested that higher ice concentrations resulting from the seeding cause aggregation growth to occur (Holroyd and Jiusto, 1971, Hobbs et al., 1972). This would not cause a precipitation decrease over a similar nonseeded storm. While the upslope systems may not be as vigorous as the other systems observed, there is no reason to assume that a similar aggregation growth process would not occur in upslope systems.

The effect of the overseeding process as well as of the other processes discussed on the total wintertime upslope cloud system sppears to be to increase the precipitation downwind of wintertime orographic cloud seeding projects.

The following conceptual model is offered as a reasonable sequence of events which is consistent with the data presented in this study and with the observations of others. The basic processes will be outlined with the aid of figure 7.1.

The seeding material generated at ground levels for the purpose of augmenting wintertime snows in the Colorado Rockies undergoes low level dispersion while it is advected into the target cloud region (Process A, in figure 7.1). If there are no clouds, or those present have high bases, a clear air transport or low level escape occurs whereby the seeding material is transported over the target ridge to the lee side of the mountain without undergoing an appreciable interaction with a cloud system. The concentration of artificial ice nuclei reaching the region during such conditions was estimated to be on the order of several hundreds per liter. If there are clouds present, the seeding material is thus depleted as it is moved through the target cloud A_2. Precipitation removal processes also act to reduce the ice nuclei concentrations. Upon exiting the target cloud the concentration of nuclei activated at temperatures higher than those along the path of the material is reduced by 90 to 95%. Concentrations under these conditions were measured to be between 5 and 60 No. ℓ^{-1}. The ice crystals nucleated by the seeding material either precipitate out or are transported to the downwind edge of the cloud. The crystals from these seeded clouds are more numerous and larger than crystals from nonseeded clouds. The material (silver iodide particles, ice crystals or a mixture of both) at the downwind edge of the cloud designated as A_3 begins a long-range transport of a distance greater than 100 km B_1. During this transport, the material will be dispersed both horizontally and vertically. In addition, any ice crystals may undergo mass changes. The sign of the mass change will depend on the local environmental moisture conditions. The material will first

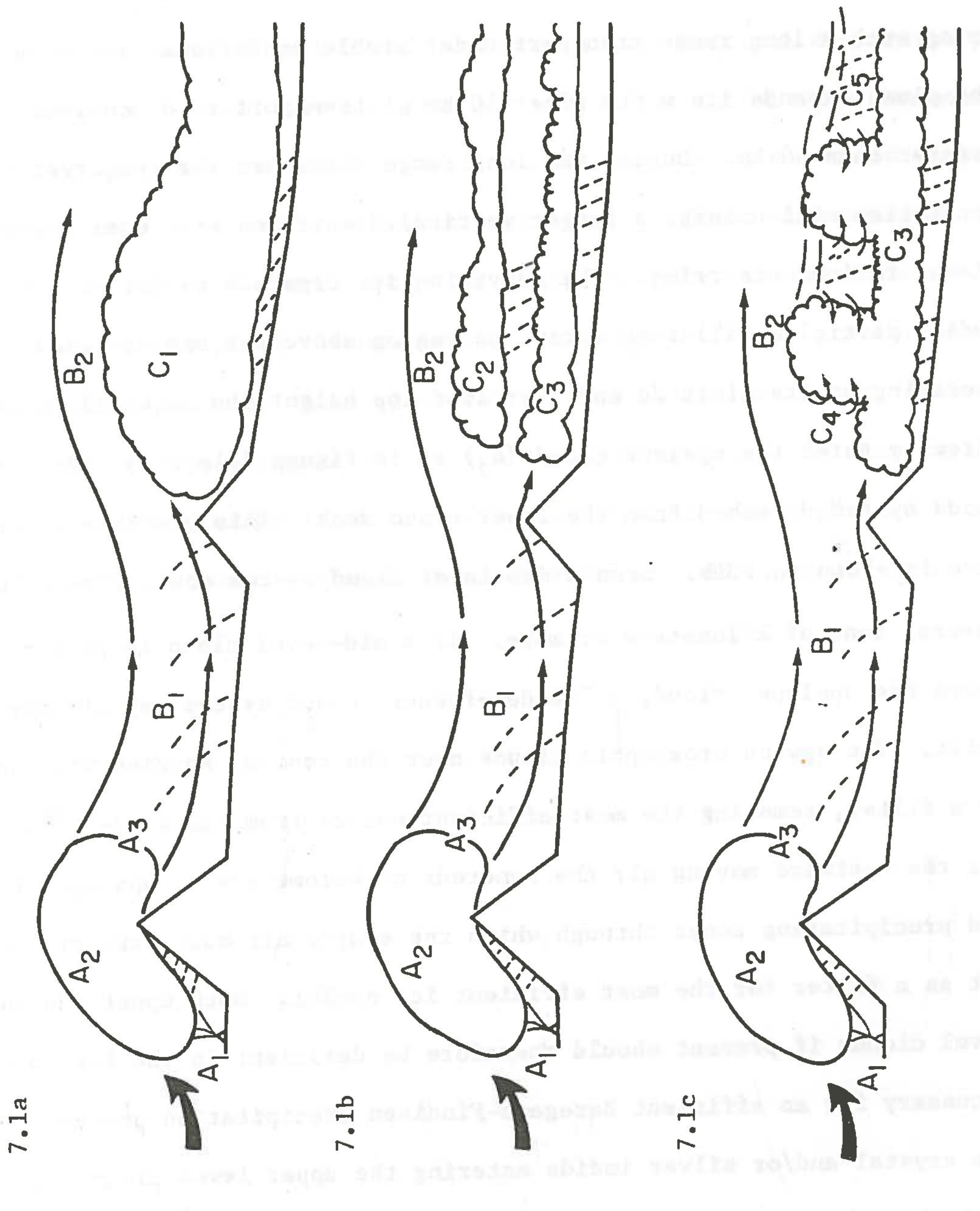


Figure 7.1. Outline of conceptual model.

undergo a downward vertical motion in the lee of the mountain ridge. It could then be subject to an upward vertical motion and wave action, depending on the environmental stability and wind speed.

The horizontal dispersion, of a plume of seeding material undergoing such a long range transport under stable conditions, was measured. The plume expands its width after 40 km of transport to dimensions greater than 40 km. During the long range transport the ice crystal population will undergo a larger vertical dispersion with some gravitational fallout occurring. The surviving ice crystals and/or silver iodide particles will then enter the region above the upslope cloud (B_1). Depending on its altitude and the cloud top height the material could directly enter the upslope cloud (B_2) as in figure 7.1a or a mid-level cloud system detached from the lower cloud deck. This possible alternative is shown in 7.1b. Such a mid-level cloud system could extend for several tens of kilometers or more. If a mid-level cloud is present above the upslope cloud, a "seeder-feeder" cloud system may already exist. The upwind orographic clouds over the central Rockies will act as a filter, removing the most efficient nuclei from eastward-moving air. For the westward moving air the hundreds of kilometers of upslope cloud and precipitating zones through which the source air must pass will also act as a filter for the most efficient ice nuclei. Both upper and lower level clouds if present should therefore be deficient in the ice nuclei necessary for an efficient Beregeon-Findisen precipitation process. The ice crystal and/or silver iodide entering the upper level cloud (C_2) would be subjected to growth, and nucleation, with subaequent crystal growth, respectively. When crystals become large enough they will fall into the lower cloud layer as in a typical "seeder-feeder" system. In this fashion the material from the clouds near Climax would increase the efficiency of the "seeder-feeder" system. The crystals and/or nuclei cloud also directly enter the upslope cloud (7.1a). They too would grow and nucleate, and, with subsequent growth, would increase the surface precipitation.

If no mid-level clouds are present and vertical dispersion processes have not brought the ice crystals and/or ice nuclei into the main body of the upslope cloud, the convective elements within the cloud could accomplish the task as is shown in figure 7.1c. These elements have radar tops over 4570 m msl. They can bring the material down into the main body of the cloud through entrainment (C_4) and/or by glaciation of the upper reaches of these elements followed by sedimentation of the crystals into the lower layers (C_5). The material entering the cloud will stimulate precipitation primarily in a "static seeding" mode through ice growth processes without appreciable dynamic enhancement of the system.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The objective of this research was to improve understanding of the physical processes which can cause extra-area precipitation alterations. The general conclusions of each phase of research are summarized below.

Evidence has been presented which ahows considerable excess ice nuclei concentrations leaving the vicinity of two wintertime orographic seeding projects in the Colorado Rockies under a variety of atmospheric conditions. These concentrations have been observed downwind some 110 to 245 km from the seeding generators. The sampling of the plumes reveals that they contain considerably more silver than the background air. However, seeding generators in Colorado are not thought to be the source. Measurements of silver concentration in the snows of the eastern plains revealed a significantly higher concentration of silver on treated as opposed to nontreated days. This evidence confirmed the extra-area transport of seeding material in an active form, and its interaction with typical cloud systems occurring in the foothills and eastern plains of Colorado.

A numerical model was developed to predict the survival time and thus the horizontal range of subliming stable and growing ice crystals. The model predictions indicate that crystals from central mountain clouds can, under some conditions, reach cloud systems in eastern Colorado. Historical and experimental studies were conducted to identify the type and characteristics of the cloud systems which predominate over the eastern plains during the winter. Upslope cloud systems were found to contribute 80% of the wintertime precipitation and approximately 20% of the total precipitation received by plains stations.

Other characteristics were also identified. Radar measurements of upslope clouds identified convective-like regions which migrate within the general cloud. These elements appeared to owe their region of origin to certain elevated topographical features. Numerical simulation of upslope cloud systems indicated that the likely response to seeding is primarily a static one with little or no opportunity for dynamic enhancement. Optimum ice crystal concentrations necessary for maximum precipitation efficiency were determined to be about 5 No. ℓ^{-1}. It was suggested that typical values of ice crystal concentration for these clouds are below the optimum level.

The physical mechanisms outlined above have general applicability to seeding experiments. However, in other types of cloud systems, mechanisms not in operation in wintertime orographic clouds may dominate over those mechanisms outlined here. This may occur to such an extent as to relegate the mechanisms investigated here to only secondary importance. In summary, a physical mechanism has been outlined and supported by a variety of studies. The opportunity for precipitation augmentation in the upslope clouds has been established. Mechanisms whereby the opportunity may be realized have also been presented.

CHAPTER IX

SUGGESTIONS FOR FUTURE RESEARCH

The research described here represents only the first step towards the understanding and utilization of extra-area effects. The mechanisms put forth will require additional field and laboratory testing as well as numerical simulation work to gain a more complete understanding of this critical area.

The measurement and collection of airborne ice crystals downwind of future weather modification experiments is essential to verify the ice crystal transport mechanism outlined here. Silver and other trace metal concentrations in snow and due to dry deposition should continue to be measured both within and without the primary target areas of new modification experiments. The addition of tracer materials to the generator solutions would greatly aid in the identification of material from modification experiments and should seriously be considered.

The utilization of AgI within clouds is not well understood. Further research should focus on this problem using both laboratory and field study approaches. Progress towards understanding the utilization of AgI within clouds can best be achieved by studying such processes in the relatively quiescent orographic cloud. To accomplish this, an aerosol sampler and a solid particle sampler should be used on flights through seeded orographic clouds. This will allow a division between activated and unactivated AgI to be made as a function of residence time in the cloud. Laboratory experiments on the nucleation process should be encouraged, with large cloud chambers being ideal for such experiments.

The upslope cloud occupies a very important position with regard to extra area effects downwind of wintertime orographic seeding projects in Colorado; yet it is one of the least investigated cloud forms. It has frequently been classed together with fogs rather than with true precipitation producing clouds. The frequency of occurrence, physical dimensions, and structure, as well as the microphysical properties of upslope clouds should be investigated.

Lastly, the transferability of the physical mechanisms described here should be tested with regard to other types of cloud systems. Some evidence gathered suggests a long range transport of seeding material does occur in hail producing clouds, but the evidence is very scarce. The results of such a study could bear strongly on the overall seeding strategy of future weather modification activities and thus merit further investigation.

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APPENDIX A

SEEDING GENERATORS

Two CSU Skyfire AgI-NaI acetone ground-based seeding generators were used during the 1974-75 winter season and one generator during the 1975-76 winter season. Generators of this type were also used during the Climax I and II experiments. The efficiency of this type of generator was recently determined during the summer of 1975 using the CSU vertical dilution tunnel and isothermal chamber. The method of such determinations is described by Garvey (1975). The results are shown in Figure A-1. Physical measurements of the effluent from these generators were made in the laboratory (Gerber and Allee, 1972) as well as in the field by Gerber _et al_. (1971, see Figures A-2). The average particle size was measured to be .04 μm (laboratory measurements). In the field the average particle size was measured to be the same. The average nautral ice nuclei (active at -20°C) size measured was 0.1 μm (Gerber _et al_., _loc cit_). The field measurements were made at a distance of 10-20 km from, and some 460-200 m above, the generator locations. At this elevation above and distance (transit time) from the generator sites one may safely assume that the aerosol had achieved a stable size distribution. That is, coagulation of very small particles and fallout of very large particles is essentially complete. Thus, the field observations represent a stable size distribution of particles entering the region upwind of the mountain ridge. The generators were located at two of the same sites used during the Climax I and II experiments; namely, Tenessee Pass and Redcliff for 1974-75 and Tennessee Pass for 1975-76. When one considers the transport of

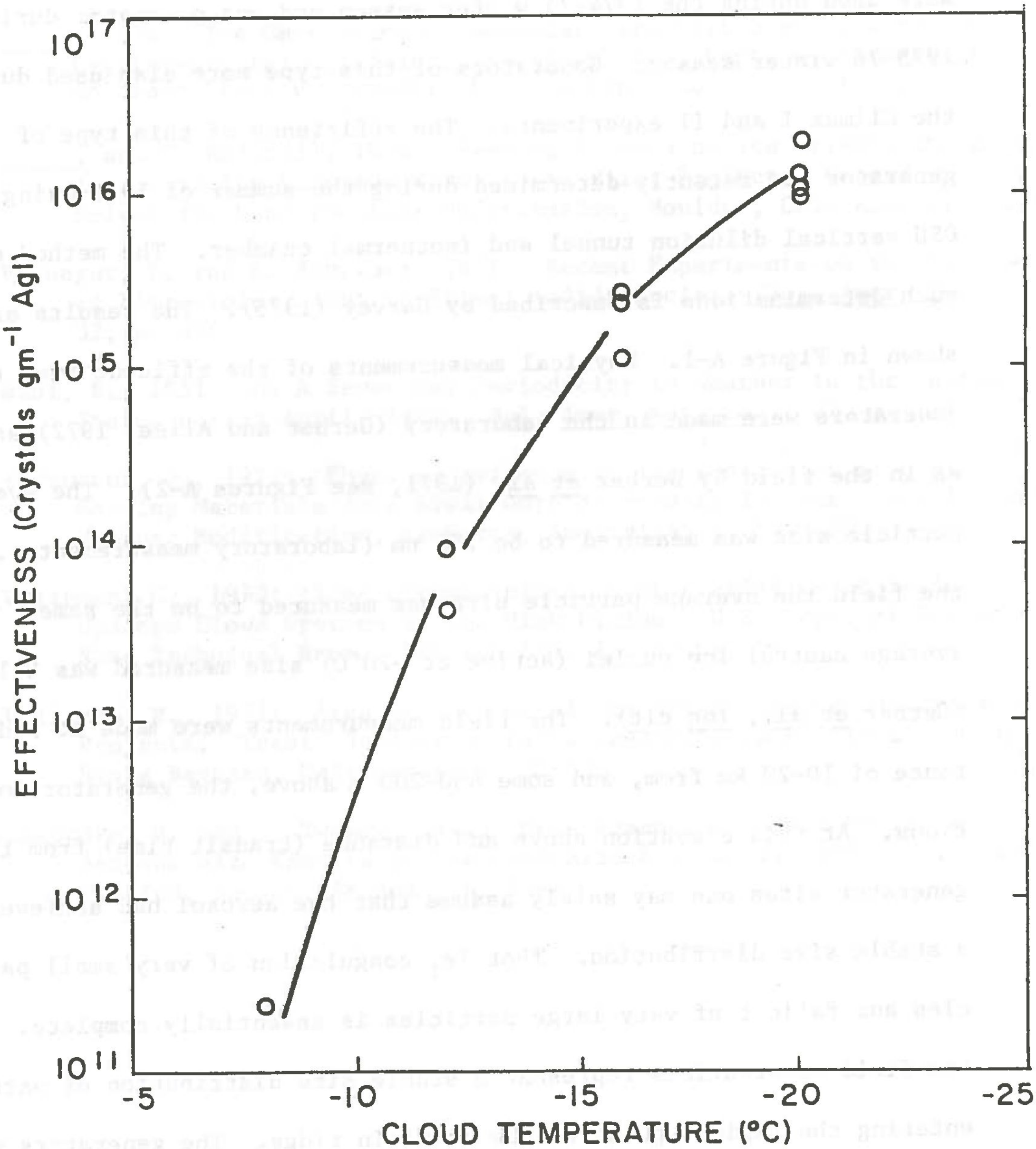

Figure A-1. Seeding generator effectiveness. CSU Skyfire ground generator, 2% AgI-NaI, 0.49 g AgI min^{-1}, maximum tunnel flow (after Garvey, 1976b).

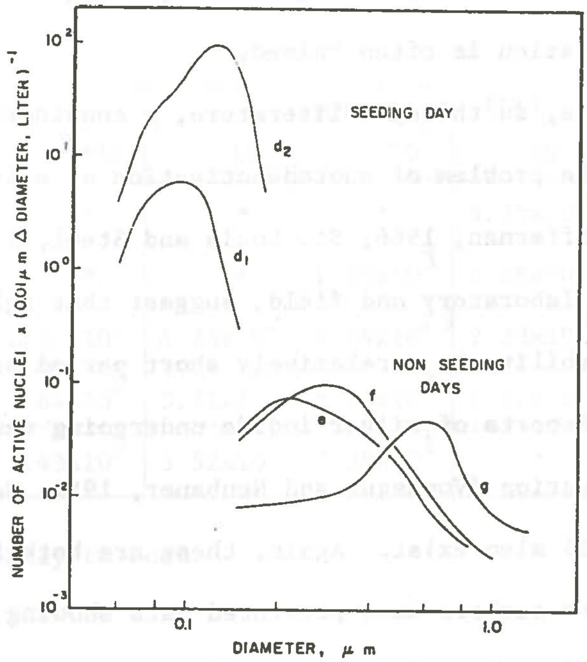

Figure A-2. The size distributions of ice nuclei (active at -20°C) measured on Chalk Mt. on a seeding day (d_1, d_2, 9/11/69) and on non-seeding days (e, 9/12/69; f, 9/16/69; g, 9/17/69). Source: Skyfire generator (after Gerber et al, 1970).

seeding material during daylight hours, the question of photodeactivation is often raised.

There is, in the open literature, a considerable body of information on the problem of photodeactivation of silver iodide (Inn, 1951; Smith and Hoffernan, 1966; St. Louis and Steel, 1968). These experiments, both laboratory and field, suggest that AgI particles lose their nucleating ability in a relatively short period of time when exposed to sunlight. Reports of silver iodide undergoing very little or no photodeactivation (Vonnegut and Neubauer, 1951; Garvey, 1975; Rottner et al., 1975) also exist. Again, these are both field and laboratory tests. Other authors have presented data showing the deactivation rate of AgI is a function of pressure and temperature (Bolton and Qureshi, 1954). The recent field observation of Rottner and the work of Garvey are generally consistent with the observations of Bolton and Qureshi.

The temperature and pressure dependence indicated by Bolton and Queshi (loc cit.) may be approximately represented by

$$t = \frac{2.6 \times 10^{+5}}{p} \exp -.082T \qquad \text{(A-1)}$$

where t is the time it takes photodeactivation to reduce the concentration of active nuclei to 10% of the initial concentration, T is the temperature in °C, and p is pressure (mb).

Table A-1 was constructed using the formula of Bolton and Qureshi (1954). As can be seen from the table, short transit times on the order of 100 to 200 minutes could seriously affect the active ice nuclei concentrations of a warm low level transport but not seriously affect a cooler upper level transport. The observations of ice nuclei concentrations made during the present research were not suitable for a

Table A-1. Time to decrease active IN concentrations to 10% of initial concentrations. time (sec.)

Pressure	Temperature (°C)				
(mb.)	+10	0	-10	-20	-30
400	*	*	*	3.35×10^3	7.61×10^3
500	*	*	1.18×10^3	2.68×10^3	6.09×10^3
600	1.91×10^2	4.33×10^2	9.84×10^2	2.23×10^3	*
700	1.64×10^2	3.71×10^2	8.43×10^2	1.91×10^3	*
800	1.43×10^2	3.52×10^2	7.38×10^2	*	*

* not likely to occur

quantitative investigation into photodeactivation of AgI nuclei. However, in view of the work of the above-mentioned authors and the qualitative observations made during this research, photodeactivation was not felt to act as a major sink of active AgI particles for processes operating during extra area effect events in the Colorado mountains.

APPENDIX B

DESCRIPTION OF ICE NUCLEI COUNTERS

The Langer acoustical counter is a continuous flowing mixing chamber type of counter. The instrument processes an air sample by first introducing a sodium chloride aerosol into the humidifying sample, then cooling it in a mixing chamber. This allows the formation of large numbers of cloud droplets during the cooling stage. The inlet air temperature is raised to about 32°C during the humidification process. This, together with the aerosol injection, insures a suitable environment for nucleation. The sample is then injected into the cool mixing chamber, which is ten liters in volume. The air is gradually cooled for about one minute before approaching the detector. During the hold-up period, nucleation can occur via vapor deposition, contact freezing, bulk freezing and via condensation followed by freezing. The sensor is a microphone which detects an audible "click" as the ice crystals (larger than 20 or 30 μm) pass through a narrowing capillary tube. The instrument responds slowly (about one minute) to large increases in ice nuclei concentrations and requires about five minutes to recover from such puffs. The normal flow rate through the instrument is 10 liter $min.^{-1}$. The counting range is from 0.5 to 9500 N. $liter^{-1}$. The instrument operates reliably below about 15,000 (4570 m) feet, but above this level it detects only a fraction of the ice nuclei which it would at lower levels.

The MEE optical counter is also a continuously flowing mixing chamber type. The air sample is humidified to saturation at a preselected temperature. The temperature of the water source for the humidification process is kept at 15°C. The sample is then injected into a cooled 3.8 liter mixing chamber. The air is thus cooled rapidly for about 15 seconds. During this time the cloud droplets form and the ice nuclei can be activated via the same mechanisms operating in the Langer counter. The sensor is an optical detection which uses crossed polarized light viewed at a 90° angle from the light source. This system is sufficiently sensitive to discriminate between ice and water particles. The instrument responds quickly (about 15 seconds) to large increases in the ice nuclei concentrations and requires about one minute to recover. The normal flow rate is 10 liter min^{-1}. The counting range is from 0.1 to 10,000 N_o $liter^{-1}$. The effects of changes in elevation are uninvestigated, except for the effects on the flow rate. Since the principal of detection does not depend on the speed of the air, the influence of elevation changes is thought to be minimal. A comparison of the two ice nuclei counters is provided in Figure B-1.

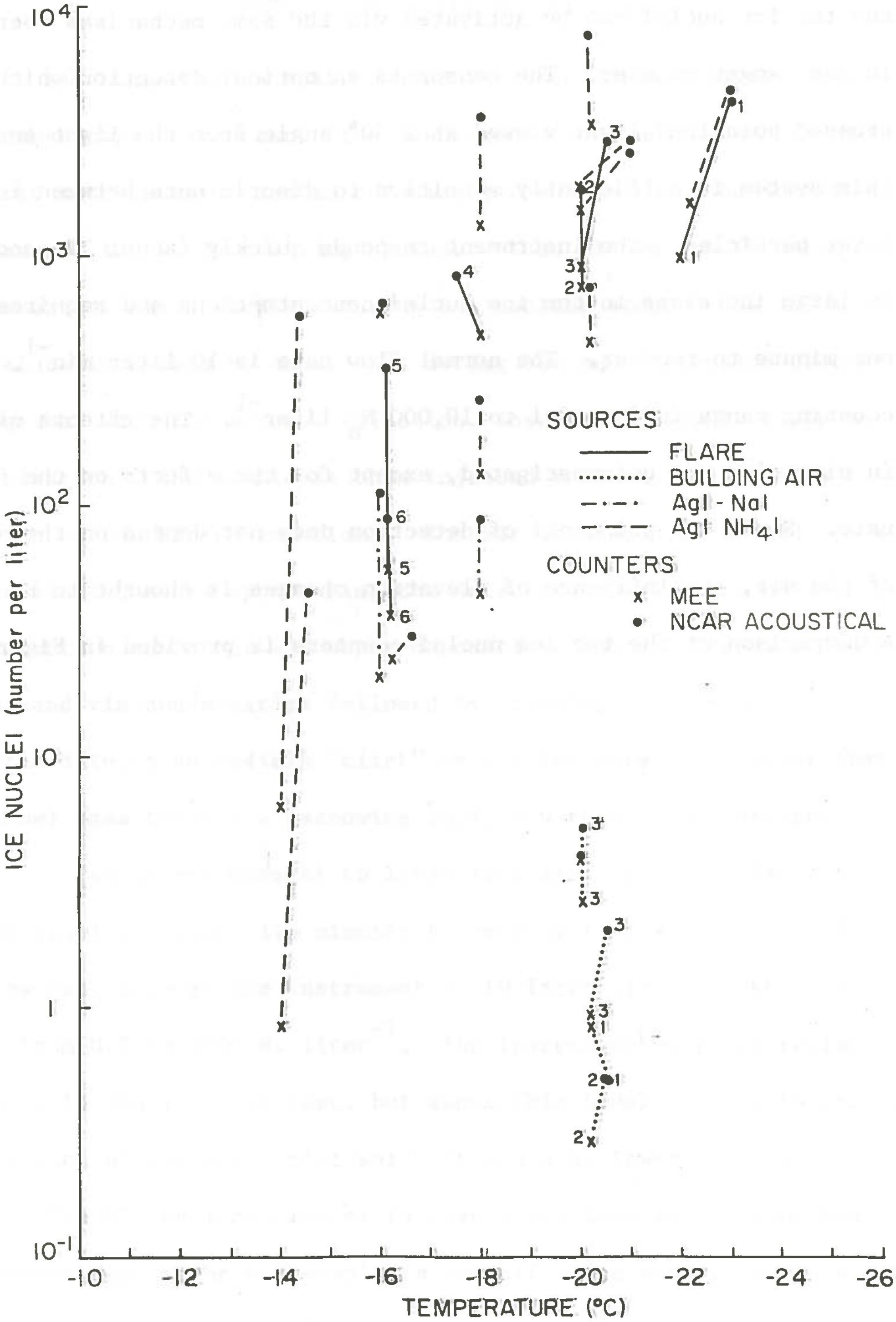

Figure B-1. Comparison of the Mee and NCAR Ice Nucleus Counter (after Garvey 1976a).

APPENDIX C

WSR-57 RADAR CHARACTERISTICS (Battan, 1973)

Wavelength	10.0 cm
Power Transmitted	450 kw
Pulse Repetition Frequency	164 Hz
Pulse Duration	4.0 μ sec
Antenna Diameter	3.36 m
Antenna Gain	38.5 dB
Vertical Beam Width	2.0°
Horizontal Beam Width	2.0°
Minimum Detectable Return Power	-110 dBm

APPENDIX D

REQUIREMENTS FOR UPSLOPE CLOUD DESIGNATION

The wind requirements for the identification of an upslope cloud were:

1. Any three primary stations reporting easterly winds and simultaneously meeting the cloud cover requirements (see Figure 6.1) or
2. Any two primary stations and one of their supporting stations reporting easterly winds and simultaneously meeting the cloud cover requirements, or
3. Any one primary station and its two supporting stations with easterly winds and simultaneously meeting the cloud cover requirements.

The sky cover requirements were that the same three stations which qualified under the wind criterion must report a sky cover greater than 0.5 (code 5 or higher). The wind and cloud cover requirements must have been satisfied for at least two consecutive time periods out of the nine total periods (00Z, 03Z, 06Z, 09Z, 12Z, 15Z, 18Z, 21Z and 00Z).

Three Denver radiosonde ascents during the nine surface observation periods were used to insure that the cloud so far isolated was not a high cirrostratus or altocumulus layer with little precipitation potential. The moist layer criterion developed was that the relative humidity must be greater than or equal to 68% for a layer more than 50 mb thick and that its base must be at or below the

650 mb level. Such a layer had to be observed for at least one sounding.

A borderline day category was established and procedures were defined to resolve the cloud type in an attempt to include the maximum number of days in the sample. A day was classified as borderline if one of the following data conditions existed:

1. The winds were reported calm at a critical surface station during a time period which could have caused the day to be declared an upslope day.
2. The data from a critical station(s) during a time period which could have caused the day to be declared upslope was missing.

The following procedures may be used to determine the cloud type if two or less stations in the period reported calm winds. If condition "1" was the reason for the classification, and if the station is question meet the cloud cover requirements, wind observations from the bracketing time periods were averaged and used as the wind for that period. If condition "2" was the reason for the classification, both cloud cover and wind direction observations from the bracketing time periods were averaged and used as the data for the missing observations. A day was classified as "ID" (insufficient data) if more than two critical stations during the day were missing. These days were not used in any analyses. Days which could not be classified by the above procedure due solely to missing wind data could be classified using radiosonde data. The Denver sounding closest in time to the missing data was used to obtain a vector average of the surface, 800 mb, 750 mb, and 700 mb level winds. This average was used in place of the missing data. The observations from Colorado Springs (COS) were not reported regularly. It was therefore used on an "as available" basis and not considered in the "ID" classification procedure. The observations from Lamar (LAA) and La Junta (LHX) were recorded under a common title and were used interchangeably with preference given to LaJunta.

BIBLIOGRAPHIC DATA SHEET	1. Report No. CSU-ATSP-276	2.	3. Recipient's Accession No.

4. Title and Subtitle

Physical Mechanisms of Extra Area Effects from Weather Modification

5. Report Date: August 1977

6.

7. Author(s)

Gerald J. Mulvey

8. Performing Organization Rept. No. CSU-ATSP-276

9. Performing Organization Name and Address

Department of Atmospheric Science
Colorado State University
Foothills Campus
Fort Collins, Colorado 80523

10. Project/Task/Work Unit No.

11. Contract/Grant No.

ERT 71-01885

12. Sponsoring Organization Name and Address

Atmospheric Sciences Section
National Science Foundation
Washington, D. C. 20550

13. Type of Report & Period Covered

Ph.D. dissertation

14. 1973-1977

15. Supplementary Notes

16. Abstracts

The physical mechanisms which could have produced extra area effects downwind of the Climax I and II wintertime orographic cloud seeding experiments were investigated. The two most probable mechanisms identified, namely, artificial nuclei transport and ice crystal transport, were studied using field observations and numerical simulations.

The field observations of airborne ice nuclei concentrations and surface silver concentrations in freshly fallen snow confirmed that concentrations of ice nuclei above background levels (AgI) were being transported at least 130 km downwind of the primary target area and were interacting with precipitating cloud systems under a variety of environmental conditions.

The numerical simulations conducted were used to evaluate the feasibility of the ice crystal transport mechanism and to study the seedability of the downwind cloud systems. The simulations showed that under certain environmental conditions, ice crystals originating in the seeded mountain orographic clouds can reach the downwind upslope cloud systems. The simulation also showed that a static seeding potential does exist for the upslope clouds.

17. Key Words and Document Analysis. 17a. Descriptors

Extra Area Effects

Downwind Effects

Weather Modification

Cloud Seeding

Cloud Physics

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 138
	20. Security Class (This Page) UNCLASSIFIED	22. Price

FORM NTIS-35 (REV. 3-72)

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USCOMM-DC 14952-P72

[illegible] December 1977 [illegible]

[illegible] Mountain Cloud Seeding [illegible]

[illegible] Atmospheric Sciences
[illegible] University
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[illegible] possible mechanisms which could have produced extra-area effects downwind of the [illegible] in wintertime orographic cloud seeding experiments were investigated. The [illegible] mechanisms identified, namely, artificial nuclei transport and ice [illegible], were studied using field observations and numerical simulations [illegible] of airborne ice nuclei concentrations and surface silver [illegible] confirmed that concentrations of ice nuclei above [illegible] were being transported at least 130 km downwind of the primary [illegible] interacting with precipitating cloud systems under a variety of [illegible] conditions.

The numerical simulations conducted were used to evaluate the feasibility of the [illegible] mechanism and to study the seedability of the downwind cloud systems. The simulations showed that under certain environmental conditions, ice crystals originating in the [illegible] mountain orographic clouds can reach the downwind cloud systems. The [illegible] showed that a strong seeding potential does exist for the [illegible].

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