ILLINOIS STATE WATER SURVEY
ATMOSPHERIC SCIENCES SECTION

DESIGN OF THE HIGH PLAINS EXPERIMENT WITH SPECIFIC FOCUS ON PHASE 2, SINGLE CLOUD EXPERIMENTATION

by

B. Ackerman: Integration of Contributions and Hypotheses
G. L. Achtemeier: Predictor Variables
H. Appleman: Review of Seeding Experiments
S. A. Changnon: User Interactions and Soclo-Economic Studies
F. A. Huff: Precipitation Measurement
G. M. Morgan: Seeding Techniques, Radar-Rainfall Measurement
P. T. Schickedanz: Statistical Design, Predictor Variables
R. G. Semonin: Operations

Final Report on HIPLEX Design Project

to

Division of Atmospheric Water Resources Management
Bureau of Reclamation
U. S. Department of the Interior
June 30, 1976

Contract 14-06-D-7197
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16. ABSTRACT

This report is the presentation of a physical and statistical design of a project for the modification of cumulus clouds to increase precipitation in the semi-arid High Plains states. The seven parts of the report include the: 1) goals, objectives, and scope; 2) scientific approach to the design; 3) required exploratory research; 4) specific design for single cloud seeding; 5) preliminary design for an area experiment; 6) impacts expected from seeding; and 7) social, economic, and environmental user interactions. Detailed descriptions of the 1) exploratory research, 2) specific statistical design for a single-cloud seeding experiment, 3) predictor variables in the High Plains, 4) previous precipitation enhancement projects in the High Plains, and 5) radar-rainfall measurement and attenuation problems are presented in Appendices A, B, C, D, and E of the report.

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I. INTRODUCTION

In early 1973, the Bureau of Reclamation Division of Atmospheric Water Resources Management (DAWRM) initiated a research effort in weather modification for the semi-arid High Plains states (Bureau of Reclamation, DAWRM, 1973). This effort was conceived as a joint effort involving local and state cooperation. It was to have four major elements: a Scientific Objective, Field Systems Test Objective, Policy Framework Objective, and Assessment Objective (op. cit.).

By spring of 1974, DAWRM had identified the modification of showery, warm-season cumulus precipitation as the initial target for research (Bureau of Reclamation, DAWRM, 1974). The experimental phases addressing the first two of the four phases mentioned above were termed the High Plains Cooperative Program or HIPLEX.

Also in 1974, the Bureau entered into cooperative agreements with interested High Plains States and selected three experimental sites, representative of the northern, central, and southern high plains. These were:

> Eastern Montana and western North Dakota, centered at Miles City, Montana.
>
> Eastern Colorado, northwestern Kansas and southwestern Nebraska, centered in the Goodland-Colby, Kansas area.
>
> Western Texas, centered at Big Spring, Texas.

In February of 1975, the Atmospheric Sciences Section of the Illinois State Water Survey (ISWS) accepted the task of developing a design for HIPLEX. HIPLEX has been envisioned as consisting of three overlapping phases dealing with (a) exploratory and background studies to provide baseline data for several aspects of the program,(b) a single cloud rain modification experiment, and(c) an area rain modification experiment. This document is concerned chiefly with the design of the single cloud rain modification experiment. Although the other two phases are treated in less detail, this is not to be construed as indicating lesser importance. DAWRM has already been provided with an exhaustive list of tasks that should be carried out to provide the background information needed for (b) and (c). These are reprinted in Appendix A. The area experiment (c) is, of course, a crucial element for achieving the overall goals of the Bureau of Reclamation. Development of the design for the area experiment has been initiated but, in view of the sequential nature of the overall program, details must await data and results from the preceding phases (see Section V).

A. Goals, Objective's and Project Scope

1. Overall Goals Set by DAWRM

The overall goals of HIPLEX, as stated by Dr. A. M. Kahan, Chief of DAWRM on 16 June, 1975 are as follows:

> "The overall goal of the High Plains Cooperative Program is establishing a verified, working technology and operational management framework capable of producing additional rain from cumulus clouds in the semi-arid Plains States (Conceptual Plan, May 1973). This goal considers improving the current operational seeding technology and enhancing confidence in its use.
>
> Baseline and cloud modification research studies will be conducted concurrently on all scales of convective activity. These studies include development of the climatology and models. Development of an expanded and improved precipitation technology will proceed from simple clouds to more complex and extensive cloud and mesoscale systems as results and concepts indicate a readiness.
>
> Because an acceptable level of scientific confirmation of the actual rain increase and the economic value of cloud seeding remain elusive, the primary program target is twofold; (1) removal of the critical physical meteorological and technical uncertainties, and (2) developing an overall certainty of confidence in producing a net benefit. The field experiments toward the first target of resolving the scientific uncertainties generally involves the design, instrument and seeding systems tests, operations and analytical efforts termed "HIPLEX" and is the main responsibility of the Bureau of Reclamation. The various associated research studies toward the second target including agricultural production assessments, environmental impact and hydrological effect studies, and economic benefit and social investigations will be undertaken concurrently with the field experiments and are the main responsibility of the cooperating state agencies for use in developing policy and management arrangements for weather modification operations. Widest possible distribution of all findings and reports is an important associated objective.
>
> The initial field program will involve a shakedown of new systems, procedures, and research teams and acquisition of preliminary data for developing experimental designs, models, and climatology."

2. Specific Objectives Adopted by ISWS in the Design Program.

This general statement was too broad to specify the goals of the experiment to be designed. Thus, the ISWS, with the concurrence of the Chief of DAWRM*, adopted the following goal and specific objectives to guide them in their design effort.

Goal

To design a scientific experiment to seek to establish the physical basis for the enhancement of precipitation of warm season convective clouds in the High Plains.

---

*Correspondence between S. A. Changnon, Jr., Head, Atmospheric Sciences Section, ISWS and Dr. A. M. Kahan, Chief, DAWRM, Oct. 27, Nov. 10, 1975.

Specific Objectives:

(a) To Increase the scientific understanding of the natural cloud and precipitation processes in semi-isolated convective entities in the High Plains and of the alterations in cloud structure and resultant precipitation that occur when these processes are manipulated in a prescribed manner.

(b) To establish the level of certainty with which these manipulations will result in the predicted alterations through a randomized proof of concept experiment (POCE) in semi-isolated simple cloud systems, with physical and statistical evaluation.

(c) To develop the physical and socio-economic baseline information needed for establishing the need for an area-wide experiment and for designing such an experiment.

Efforts directed toward meeting these objectives are to be carried out concurrently with the realization that, as it becomes available, knowledge gained from work under (a) above will influence the efforts under (b), and the knowledge gained from work under both (a) and (b) will influence the effort under (c).

3. Uncertainties in Weather Modification

A primary program target of HIPLEX is the reduction of meteorological and technological uncertainties in weather modification. That many unknowns exist is obvious from the mixed results of past modification experiments with convective clouds, in both target and extra-area rainfall.

There are major uncertainties with respect to the particular types of convective cloud conditions which provide opportunities for modifying the precipitation, and the stage(s) in the cloud evolution during which alteration in the microphysics should be effected. Equally critical, however, are the questions associated with the uncertainties in the social impacts which will prescribe the type of precipitation modification desired. That is, if precipitation enhancement is the objective, is it desired as increased rainfall rate, duration, or areal extent? Problems associated with these areas of concern are:

- Large- and meso-scale dynamic conditions which control convective development
- Magnitude, location, and continuity of the supply of water vapor
- Supply and local concentrations of natural ice and condensation nuclei
- Productivity and timing of the natural, unmodified, rain-producing processes and the dominant rain-producing process
- The mechanisms of ice formation in clouds and their requirements for activation.

There are also major uncertainties as to the ultimate disposition of the seeding material once it has been generated and, in particular, its characteristics and spatial dispersion at the level at which it is to alter the microphysics. Assuming that the capability of generating seeding material in the desired physical form and concentration is a solvable engineering problem, the problems contributing to these uncertainties are:

Dispersion of the material from the line (or point) source and the related questions about the air motions around the source and in and around the clouds.

Role of scavenging and coagulation in changing the concentration and character of the material.

Deactivation, or reduction of activation efficiency, before the material can enter into the evolution of the cloud, microphysics.

There are critical uncertainties concerning the cloud response to the altered microphysics, and the relationship between the cloud response and the amount and character of the precipitation produced at the ground. The objective of the seeding is usually to bring about one or both of two primary cloud responses: a) increased buoyancy acceleration due to release of latent heat and b) collection of existing suspended condensate so that it will fall to the surface. The interaction between the microphysics and dynamics of the cloud is a central factor in determining the rain productivity. Questions that contribute to the uncertainties in the cloud response to the altered microphysical changes are:

- Conversion rate of cloud to precipitation particles
- Spread of the conversion through the cloud volume
- Role of ice multiplication processes in the conversion of water to ice
- The modified vertical velocity profile and the continued supply of moisture to the accelerated cloud regions
- The vertical transport of the modified condensate in the accelerated cloud regions (i.e., is the condensate carried out of the active cloud top into a cirrus deck)
- The effect of induced or accelerated sedimentation of the suspended condensate on the updraft velocity in the lower regions of the cloud and consequently on the flow of moisture from the usually more humid lower atmospheric regions to the upper cloud levels.
- The raindrop spectrum produced at cloud base and subsequent change during its fall through the subcloud air to the surface.
- The alteration, if any, in the duration of the moisture-processing and rain-producing stages of the cloud.
- The alteration in the cloud dynamics and microphysics and rain production if the ice phase is altered in clouds in which the coalescence process dominates, or vice versa.

Another group of uncertainties concerns the extension of the effect of the local modification, <u>if any</u>, beyond the limits of the seeded cloud and the net effect on the total surface precipitation over both nearby areas and more distant downwind areas.

- Some of the factors that lead to the uncertainties are:

- Modification of the physical state and kinematics of the nearby environment and the subsequent effects on new cell (or cloud) development, on dissipation (or development) of nearby clouds, and on mergers with adjacent clouds.
- Effect of altered in-cloud rain characteristics on the downdraft and subsequent effect on moisture inflow into adjacent clouds and on initiation of new cloud-forming updrafts.
- Effect of vertical redistribution of energy, if vertical exchange is enhanced, and the sphere (space and time) of influence.
- Amount of seeding material which did not enter the target cloud and/or remains suspended as an aerosol after the target cloud dissipates and its effect on the subsequent cloud and precipitation development, locally and downwind.
- Possible transfer of seeding material from target cloud cell to other cells or other clouds
- Propagation of cloud development dynamically if the class of convection is significantly changed (e.g., from cumulus congestus to cumulo-nimbus)

A final area among the physical and technological uncertainties, and perhaps the most crucial of all, is in the realm of proof — how to distinguish between modified and naturally-occurring phenomena. One major problem lies in the difficulty of predicting the natural cloud behavior and rain productivity. A parallel problem occurs in predicting how the altered cloud behavior and productivity differs from the natural case. Many of the uncertainties and problems which have already been listed apply to the natural as well as the modified case, for once the alterations in the microphysics have taken place, the subsequent cloud behavior is the same as would have occurred if the new microphysical state had taken place naturally.

Lacking this capability to predict natural behavior, is it adequate "proof" to demonstrate, through measurements, differences between seeded and unseeded populations? Problems arising here lie in:

- Sampling so as to produce unbiased, uncorrelated seeded and unseeded samples
- Accuracy and representativeness of the measurements
- Establishing the level of significance which is acceptable
- Identification of key parameters to measure which would be accepted as demonstrating seeding effect if significant differences were found
- Identifying appropriate and sensitive statistical tests

This list of physical uncertainties and questions is a lengthy one and poses many difficult problems. It would require persistent, extensive and continuous efforts to solve them. Indeed, in many cases the capability does not exist at this time to obtain solutions. Obviously HIPLEX can hope to resolve only a very few of these questions, and shed some light on a few others. Accumulated evidence indicates that seeding with ice nuclei sometimes leads to increases in precipitation, sometimes to decreases, and sometimes has no effect on precipitation. A major contribution to reduction of the uncertainties would be identification of conditions determining which of the three will be the outcome of seeding for alteration of the natural cloud glaciation.

The other primary target of HIPLEX, establishing net benefit, also presents many questions. The uncertainties associated with the social, economic and environmental aspects are even more numerous than the physical ones because of the many complex issues which are involved. The key uncertainty lies in how to estimate the aggregate benefits and disbenefits of modification within the total social, economic and environmental context. The problem is extremely complex because what may be a benefit to one interest group may be a disbenefit to another interest group, particularly if modification extends over large heterogeneous areas. And how does one assess a value to intangibles, such as changes in natural flora and fauna (if they occur) or in public attitude? Most of these complex issues have never been addressed in weather modification, but they are considered an essential part of HIPLEX (see Section VII).

4. Program Scope - ISWS

The uncertainty of the precipitation enhancement capability for convective clouds obscures the possible economic benefits. The minimization of this uncertainty is an integral part of the HIPLEX objectives. The agricultural, water supply, and energy-saving economic implications justify the increased probability of success of convective cloud modification expected from this program.

Although the overall economic impact of rainfall enhancement from semi-isolated cloud systems is uncertain, significant benefits will result from the increased understanding of the processes involved in the modification." The expanded body of knowledge expected from a scientifically-oriented single cloud experiment helps the development of an area-wide experiment by shedding light on the mechanisms by which the precipitation may be modified. Thus, in accordance with the strategies outlined in the 1974 DAWRM plan (op. cit.) and with subsequent statements by DAWRM, the single cloud experiment is the main focus of the work undertaken initially by the Illinois State Water Survey.

"Complete management of the atmospheric water resources of the High Plains includes the potential for reduction of precipitation under certain circumstances when it might be potentially advantageous. However, the largest fraction of the potential benefits are to be expected from enhancement, not reduction, of precipitation. Thus the concept of precipitation reduction was <u>not</u> considered among the ISWS design objectives.

The design effort undertaken by ISWS incorporates a sequential scientific approach to define the capability 1) to enhance the precipitation from individual clouds, and then 2) to enhance the precipitation over an area as a consequence of the augmentation of precipitation from individual clouds and cloud groups. The capability is to be developed for the modification of the cumuliform clouds most prevalent during the warm season throughout the High Plains region.

The recommended experiment consists of two components: an atmospheric effort and a socio-economic and environmental effort. The experimental components are divided into phases consistent with the sequential scientific endeavors (Figure 1). The parallel efforts in Figure 1 are essential for the full realization of the scientific and socio-economic potential of the program.

The exploratory studies (Phase 1) define the problem within the scope of available knowledge and technology. These studies develop the body of knowledge and observations needed for both the single cloud and area experiments. Simultaneously, the available knowledge of the socio-economic and environmental conditions pertinent to the HIPLEX region will be assembled and the development of concepts and models will be initiated.

The *single aloud rain modification experiment* (Phase 2) is concerned with the precipitation from single, semi-isolated convective entities. It consists of two efforts: an *initial effort* in which hypotheses are tested and systems are field tested, and a *second effort* which is a proof of concept experiment (POCE) which will establish the physical basis for precipitation enhancement for cumuliform clouds. Monitoring of the socio-economic impact of the experiments will be initiated concurrently with the field program. A major result from the single cloud modification phase will be the scientific understanding on which to base the formulation of a hypothesis for rain enhancement over an area (Phase 3).

The *area rain modification experiment* (Phase 3) will be carried out according to hypotheses developed from the Phase 2 results. It will consider precipitation from convective cloud systems as well as individual convective clouds. A new evaluation procedure will be developed and the final impact assessment will be performed. The program is envisioned as continuing through Phase 3, unless the findings of the socio-economic component of the research or of the Phases 1 and 2 of the atmospheric component should indicate that Phase 3 is unwarranted. Phase 3 will conclude the HIPLEX research effort.

Subsequent action of the DAWRM and the states will involve the transfer of the developed technology (Phase 4) to all applicable areas within the High Plains region.

B. Management

HIPLEX consists of cooperative efforts jointly supported and directed by the Bureau of Reclamation and various agencies of the states involved. HIPLEX had been developed by DAWRM *prior to this design* as a 3-area research program

COMPONENTS OF HIPLEX - RAINFALL ENHANCEMENT

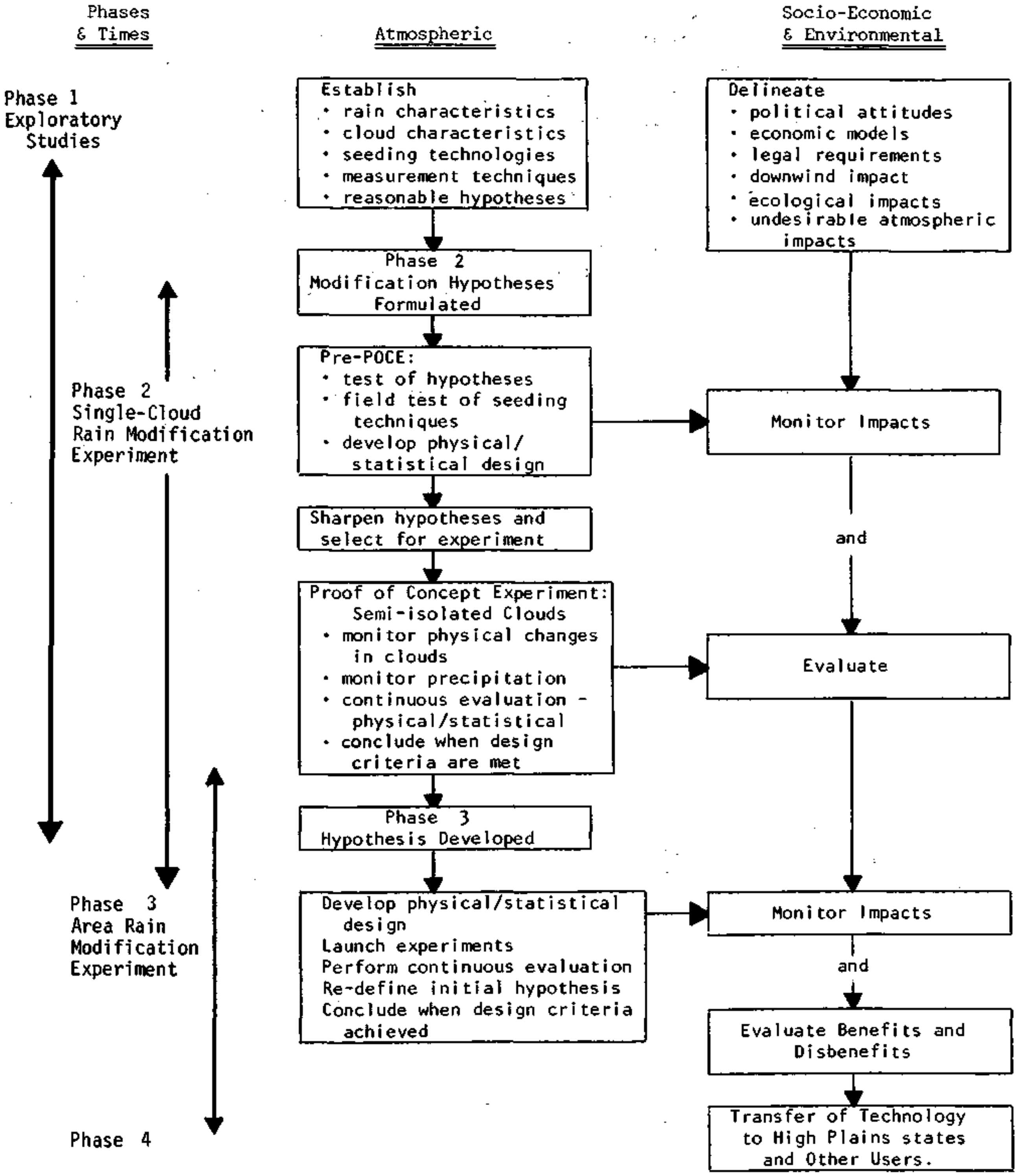

Figure 1. Flow of experimental effort in HIPLEX.

to provide data and results representative of the northern, central, and southern plains. Thus, HIPLEX will

(a) provide meteorological results representative of all climatic zones of the High Plains;

(b) sample and interpret economic, social and geopolitical differences; and

(c) provide data and tests for translation of the final results throughout the High Plains.

The relative roles of the states will vary depending on state interest and funding. This will range from a large degree of autonomy in carrying out the experimental work plan to nearly complete Bureau of Reclamation direction and implementation. The degree of Bureau and state management should vary to accommodate local interest and involvement, but the Bureau of Reclamation (DAWRM) should have ultimate design and performance responsibilities.

In order to insure that all activities in HIPLEX are coordinated and that they follow the program design, the table of organization shown in Figure 2 is recommended. A Project Director should be designated who is responsible only to the Chief of the Division of Atmospheric Water Resources. His responsibilities may be grouped into three general areas: atmospheric studies, socio-economic and environmental studies (SEES) and management functions. He may elect to delegate all or part of the responsibilities in one or more of these areas to others in DAWRM or to a contractor. The atmospheric studies and SEES may be under different management at the three sites but there must be communication and coordination where appropriate and possible between these activities at both the local level and the upper management level.

The Project Director has overall responsibility for implementation of the design and for seeing that a detailed work plan is developed. He should provide for liaison and cooperation where appropriate with other experimental weather modification projects, particularly those in the High Plains (e.g., NHRE) and should seek advice from consultants and advisory panels.

C. ISWS Design Considerations

A number of diverse factors have had to be considered by ISWS-in developing this design document. These ranged from defining the ISWS role in HIPLEX to dealing with the reality that certain actions had already been taken by DAWRM. Some of these factors are listed below.

(a) The role of the ISWS in HIPLEX is best envisioned as that of a consultant group, providing an initial plan and guidance for modification of the design elements as results become available.

(b) The ISWS design responsibility is viewed as total, and in the pre-design considerations we have assumed that no design decisions had been made. In this framework, that which has been done can be judged with all other options and retained, or discarded, as the weight of the evidence indicates.

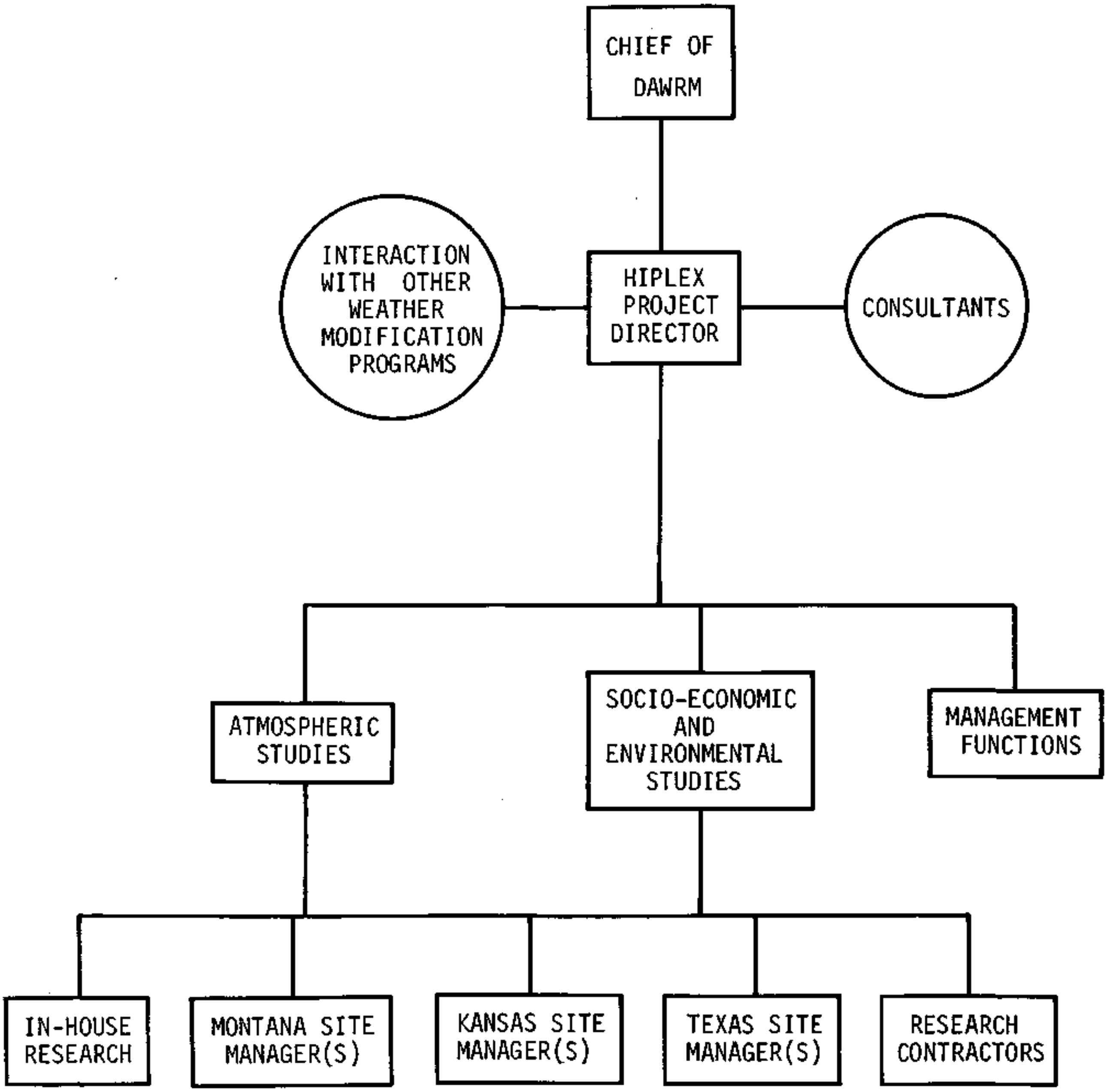

Figure 2. Recommended table of organization for HIPLEX

--) There has been more than two years of prior DAWRM and state planning, organizing of field activities and in-house research, and commitments to sites, equipment types, and other components involved in the management and research.

(d) The design makes every effort to accomodate

- diverse state and federal commitments, including sites previously selected and extensive equipment already procurred,
- on-going operational and experimental modification projects, with possible utilization of results from these projects,
- fluctuations in levels of annual funding, and
- results from past operational programs and experiments in the High Plains, so as to develop coherent technology ultimately transferable to all parts of the High Plains.

(e) The design effort addresses all facets of two questions: Can it be done? and Should it be done?

(f) Ultimately the success or failure of any rain alteration, either from individual clouds or over an area, is in terms of human benefit and rests on consideration of socio-economic factors, although certain meteorological findings alone can be of great scientific value.

(g) The key aspect of the atmospheric phase of the design is the sequential experimental approach based on sound scientific research. Shifting from background and field studies of clouds and precipitation to a series of proof of concept experiments *should occur only when critical unVnowns are removed, allowing physically sound hypotheses appropriate to the High Plains to be developed and tested.*

II. APPROACH

A. General

The experiment should be research-oriented, and should seek answers to the following problems:

- When, how, and by what means is convective precipitation altered (modification hypothesis).
- What is the change in precipitation and what is degree of certainty of the change (test and evaluation).
- Is it economically beneficial and socially acceptable (societal impacts).

The program should be comprehensive, and universal in the sense that it is applicable to any part of the High Plains. It becomes site specific as a detailed design and work plan are developed, based on local meteorological, economic and sociological conditions.

If resources are not sufficient to carry out the comprehensive program at all three sites, the following actions will best serve the goals of HIPLEX. First, the comprehensive program should be implemented at one, primary experimental site, before proceeding to another in lieu of diffusing the resources and mounting subcritical efforts at two or three locations. Secondly, if funds are insufficient to carry out the full program well at a second location, the efforts at the sites(s) other than the primary one should be directed toward the collection of the critical measurements for establishing transferability. The primary site should be carefully selected, with local meteorological and cloud conditions and representativeness for the High Plains given priority consideration.

An adequate level of funding and effort should be allotted to analysis of data as they are obtained to ensure adequate, year-to-year procurement of in-depth results of critical conditions needed to move sequentially through the first three phases (Fig. 1). A suggested division would be 60% for analyses and 40% for field effort.

B. Exploratory Studies, Phase 1

A major effort in this Phase is essential for the development of suitable designs and work plans for both Phase 2 and Phase 3 seeding experiments. The meteorological information currently available for most of the High Plains is not adequate for the development of specific modification hypotheses or of monitoring systems. In some instances the basic data are available but not accessible in an easily usable form; in other instances the necessary meteorological observations are not available. Efforts to alleviate some of the information gaps have been initiated within ISWS and by DAWRM, in-house and by contractor. These efforts must continue through the duration of Phase 2 .

The essential studies are problem-oriented, addressing the major components of rain modification experiments:

(a) Seeding Experiments:

- Formulation and selection of modification hypotheses (physical studies of cloud and precipitation characteristics and their frequency).
- Selection of modification techniques (investigation of seeding technologies) and prediction of the consequences of treatment.
- Identification and prediction of conditions suitable for manipulation of the precipitation process.
- Measurement and evaluation of alterations (study and selection of measurement techniques, test parameters, and statistical design).

(b) Atmospheric impacts within and extending in all directions from the treatment target area.

(c) Assessment of benefits and disbenefits: economic, social, and environmental, to derive the net socio-economic value.

C. Single-Cloud Rain Modification Experiment, Phase 2

Phase 2 is concerned with the establishment of an acceptable level of scientific certainty of the consequences of modification efforts on relatively simple, semi-isolated cloud entities. These entities may be single or multi-cellular, of limited horizontal extent and separated from other such entities by significant distances (one or more cloud diameters).

In Fig. 3 are summarized the background atmospheric studies* which should be carried out before a proof of concept experiment (POCE) is undertaken. They provide the basis for selection of final hypotheses, technologies and evaluation procedures. Although the list may appear formidable, it is not unrealistic and many of the studies are already underway. All of the studies are important, and tasks 1, 5 and 7 are essential. If funding absolutely requires it, task 8 may be limited or dropped. Although these laboratory studies would be useful, they are not essential for the POCE. The indicated number of cases (years, clouds) on which the studies should be based are estimated from cloud and rain conditions in the Middle West. These are believed to be realistic but the exact number will depend on the variability of the clouds and rain in the High Plains.

Phase 2 contains the following elements:

(a) Test of hypotheses and final selection of a limited number for a full scale proof-of-concept experiment.

(b) Field test and selection of seeding technique(s).

*Figure 14 (Section VII) gives the milestones that need to be reached in the non-atmospheric studies.

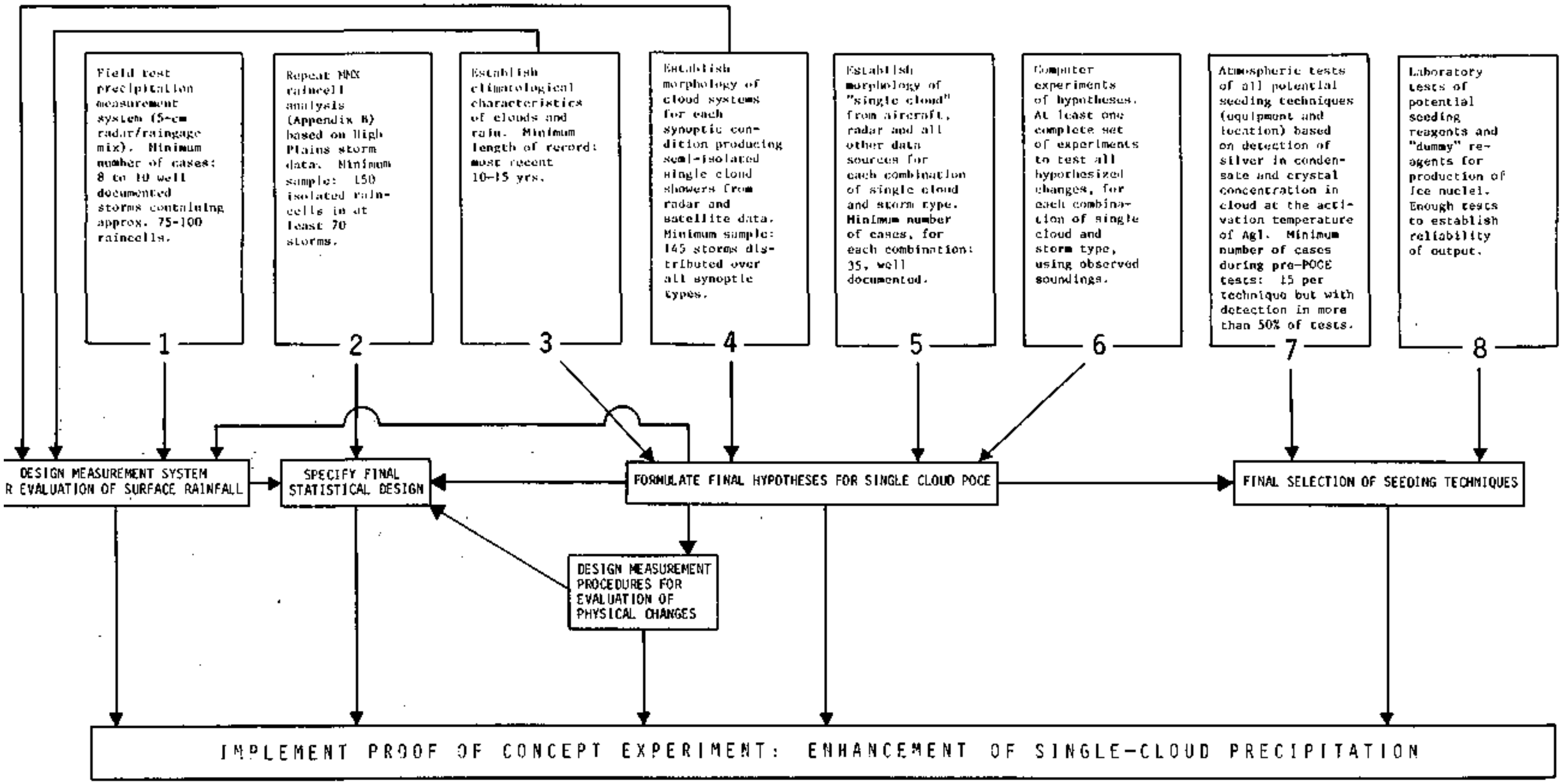

Figure 3. Flow chart showing the exploratory studies which have to be carried out and decisions which have to be made before the single cloud seeding experiment can be started. Also shown are approximations of the number of cases which have to be included in each study area. These approximations *are* based on the cloud, storm and precipitation characteristics in Illinois and may have to be revised as data become available from the High Plains.

(c) Design and implementation of a modification experiment (POCE) on relatively simple, but probably multi-cellular, semi-isolated clouds with physical and statistical evaluation.

(d) Development of background information needed to refine the design of a single cloud experiment and to design full-scale area-wide seeding experiment.

(e) Monitoring of social, economic, ecological, and extraneous atmospheric impacts during experiments.

D. Area Rain Modification Experiment, Phase 3

This phase is concerned with developing an overall level of confidence in producing a net benefit from efforts to modify cumuliform clouds, semi-isolated or embedded in systems, over an area. Progression from Phase 2 to Phase 3 depends on attainment of the goal of Phase 2, i.e., reaching an acceptable level of certainty that the outcome of the deliberate modification will be as expected. Ultimately the decision as to what is an acceptable level must rest with those who will be running the risk of being wrong, namely DAV/RM. It is the recommendation of the design group that HIPLEX advance to Phase 3 only when the most sensitive of the statistical tests that can be devised show significant results and these results are supported by physical theory. Acceptable Alpha levels would lie between .05 and 0.10, with .05 preferred, and Beta levels between 0.10 and 0.30 would be reasonable.

Phase 3 contains the following elements:

(a) Assessment of the physical and seeding hypotheses, economic cost-benefit ratios, and environmental and extra-area physical impacts.

(b) Design and implementation of experiment if overall capability and benefits are indicated from Phase 2 and from the socio-economic studies.

(c) Evaluation by physical and statistical methods.

E. Transfer of Technology to Users, Phase 4

Phase 4 is the final element of the program. The Bureau of Reclamation, in coordination with the interested states, should disperse as widely as possible full details of the results of the experiments and the developed technology.

III. TECHNICAL EXPLORATORY STUDIES

Research studies to develop adequate background information on rain and cloud climatology, cloud and cloud system characteristics and seeding techniques are an essential part of the experiment. In some instances, they must be completed before the POCE segment of Phase 2 (Figure 3).

DAWRM has been provided with several sets of recommendations for studies needed for the major components of the seeding experiments. These recommendations are reprinted in Appendix A. The sequence of these exploratory studies is shown in the flow chart in Fig. 4.

More specifically-stated tasks, grouped by research area, and their objectives are shown diagramatically in Figures 5-10. Some of the recommended tasks already have been undertaken by DAWRM personnel, by other DAWRM contractors, or by the design group at ISWS. Most of the studies made by the ISWS have been for internal use in formulating the design. Some are summarized in accompanying Appendices.

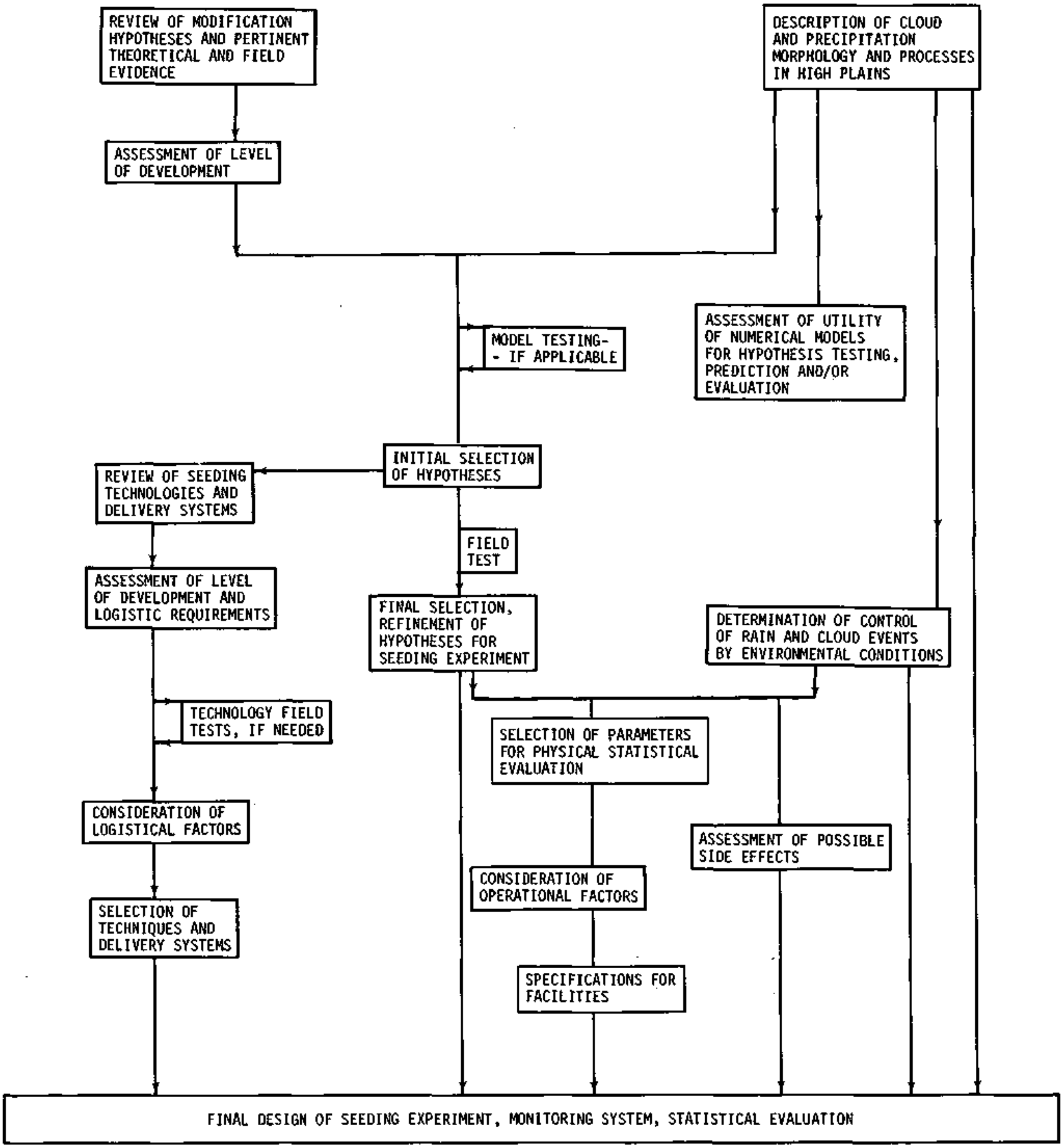

Figure 4. Technical exploratory studies and decisions needed for the final design and implementation of the proof of concept experiments.

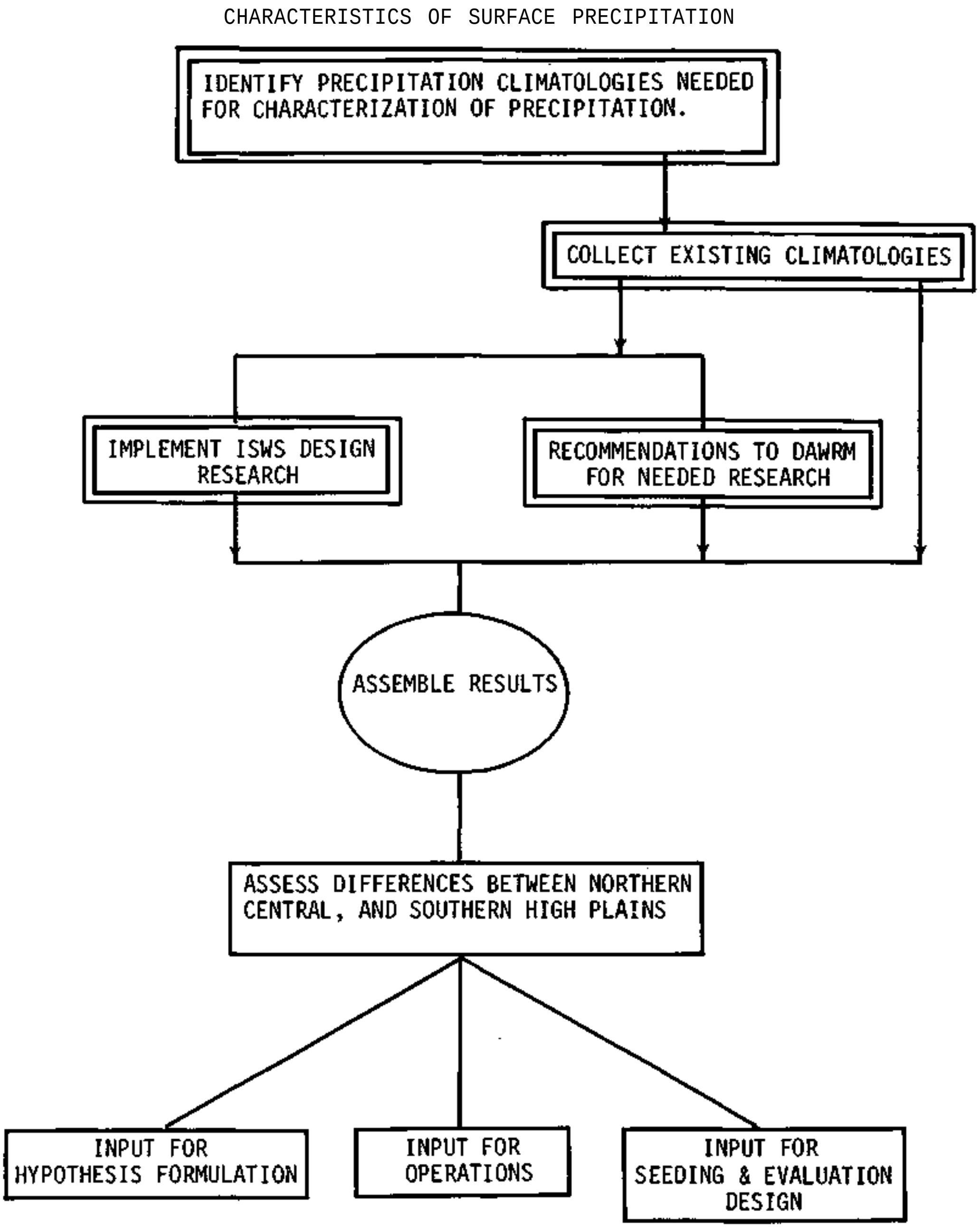

Figure 5. Exploratory studies needed to describe the characteristics of the surface precipitation. Tasks undertaken by ISWS for design purposes are indicated by a double box.

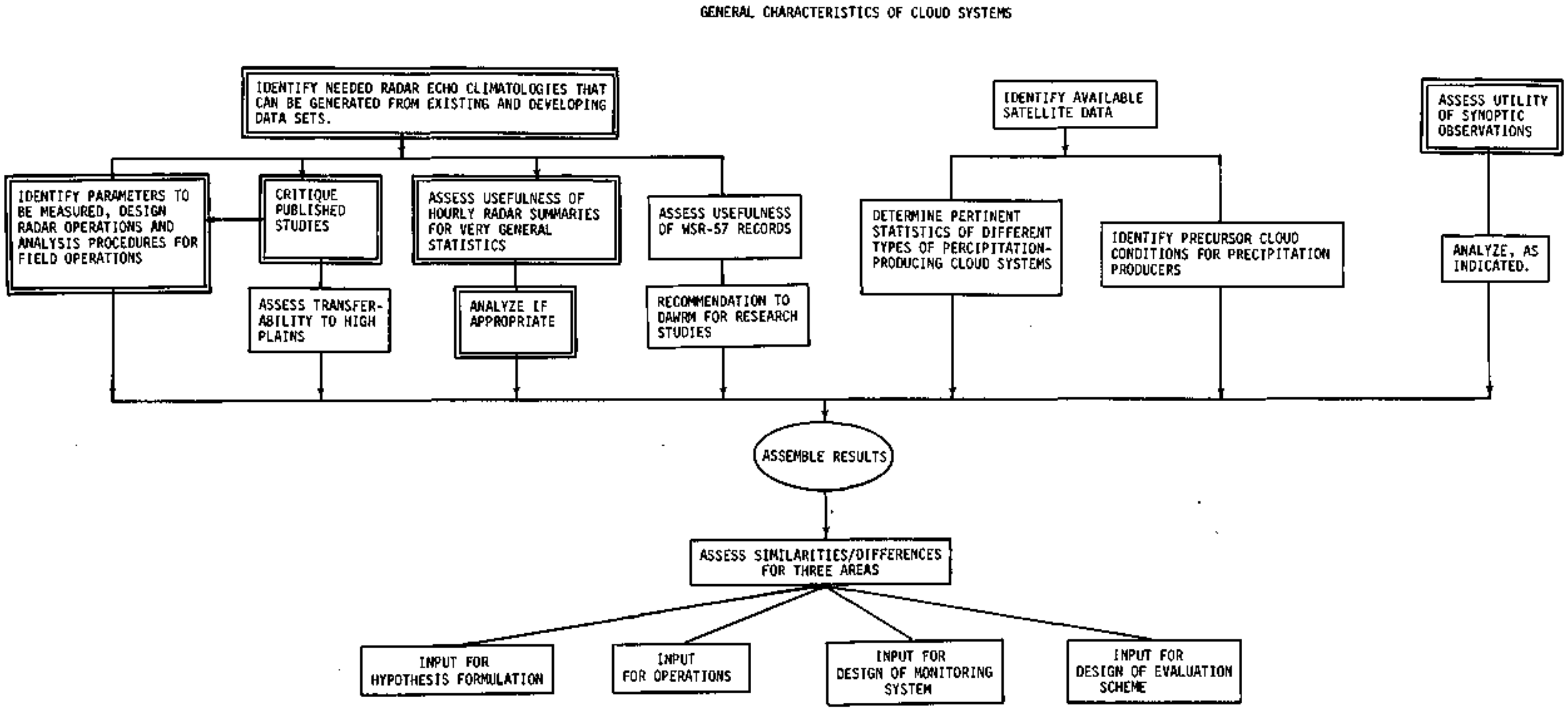

Figure 6. Studies needed to describe the characteristics of the High Plains cloud systems. Tasks undertaken by the design group at ISWS for design purposes are indicated by a double box.

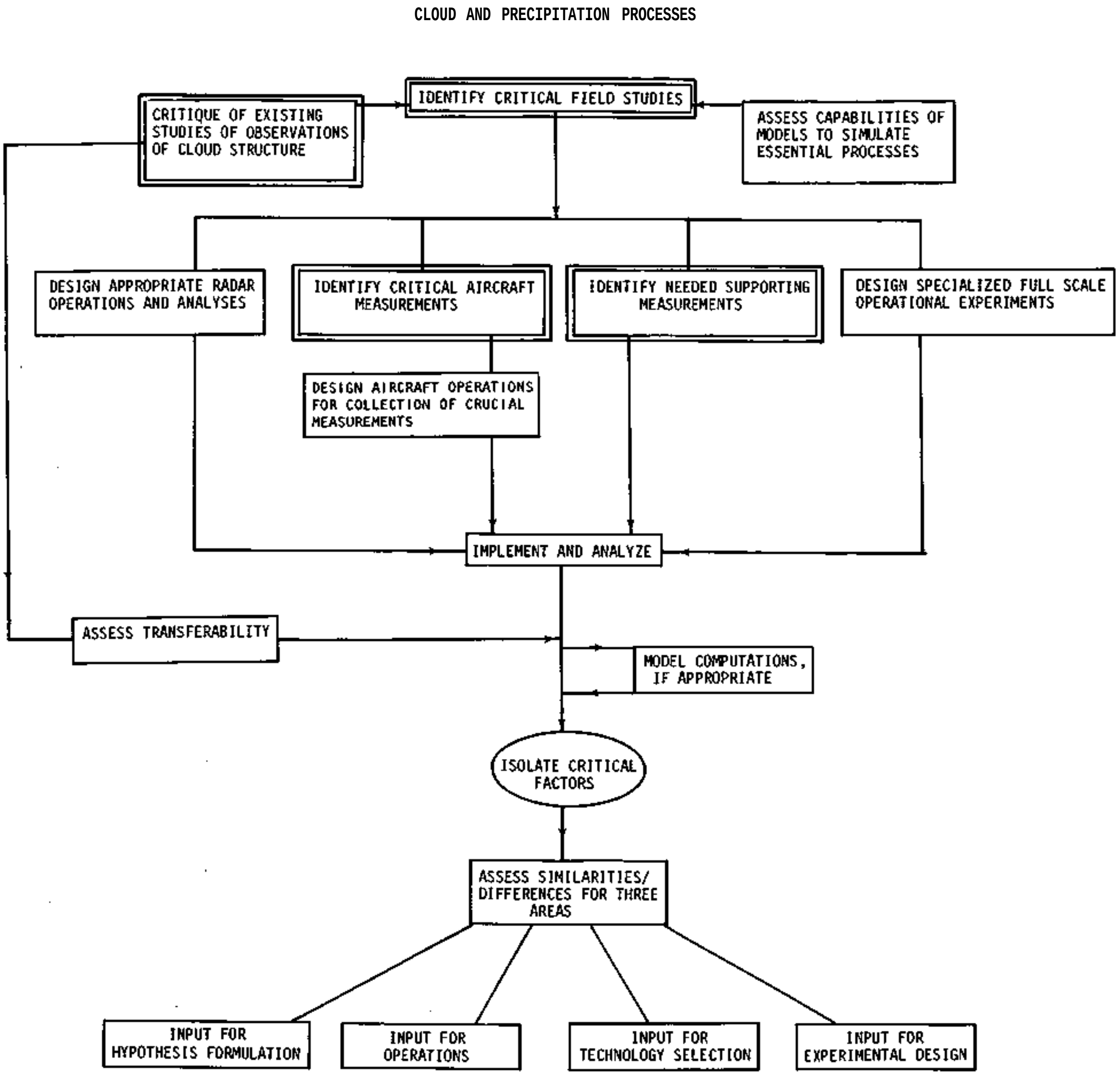

Figure 7. Studies needed to determine the cloud and precipitation processes in High Plains clouds. Tasks undertaken by ISWS for design purposes are indicated by a double box.

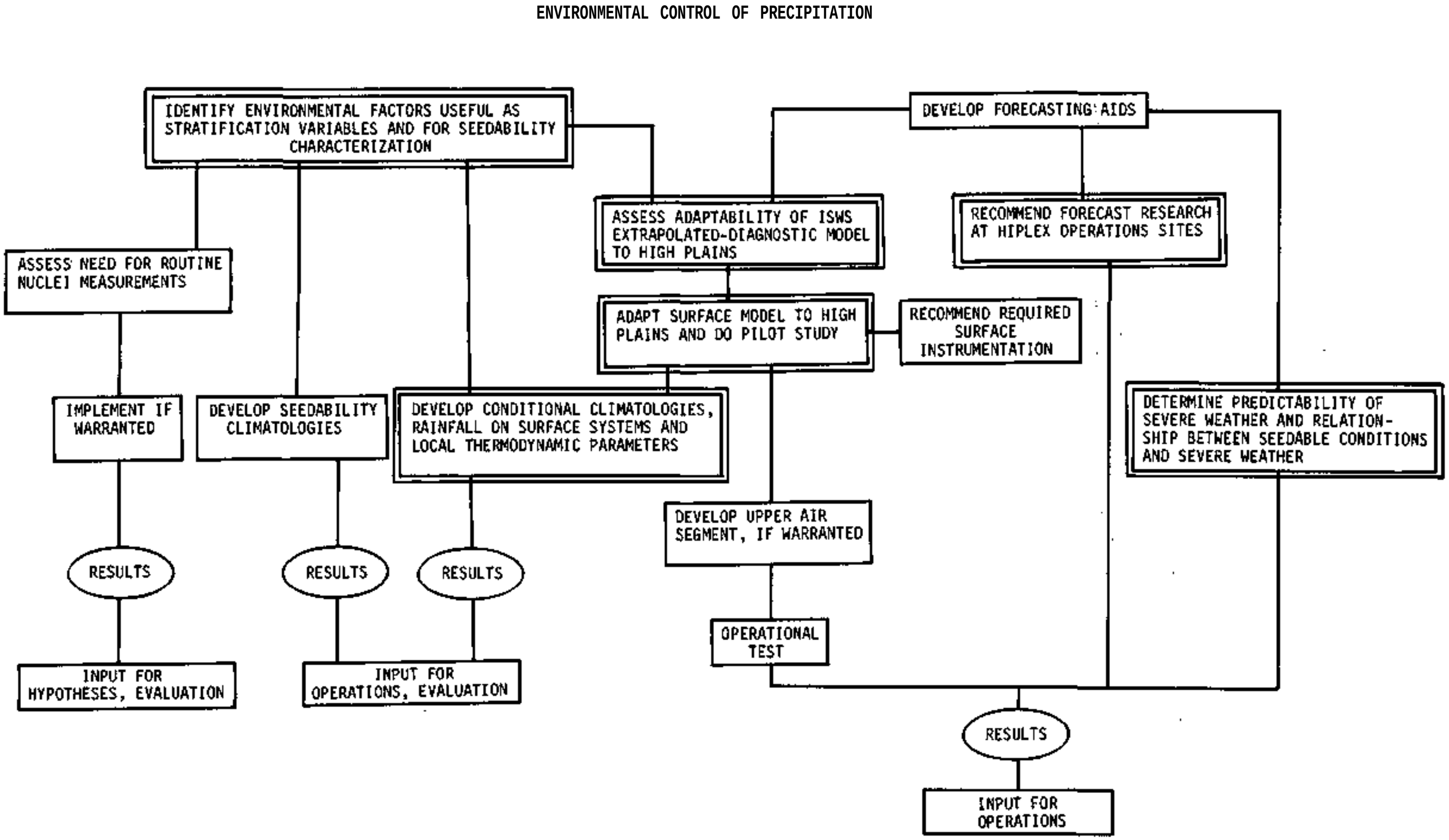

Figure 8. Studies needed to establish environmental control of convective precipitation in the High Plains. Tasks undertaken by the design group at ISWS for design purposes are indicated by a double box.

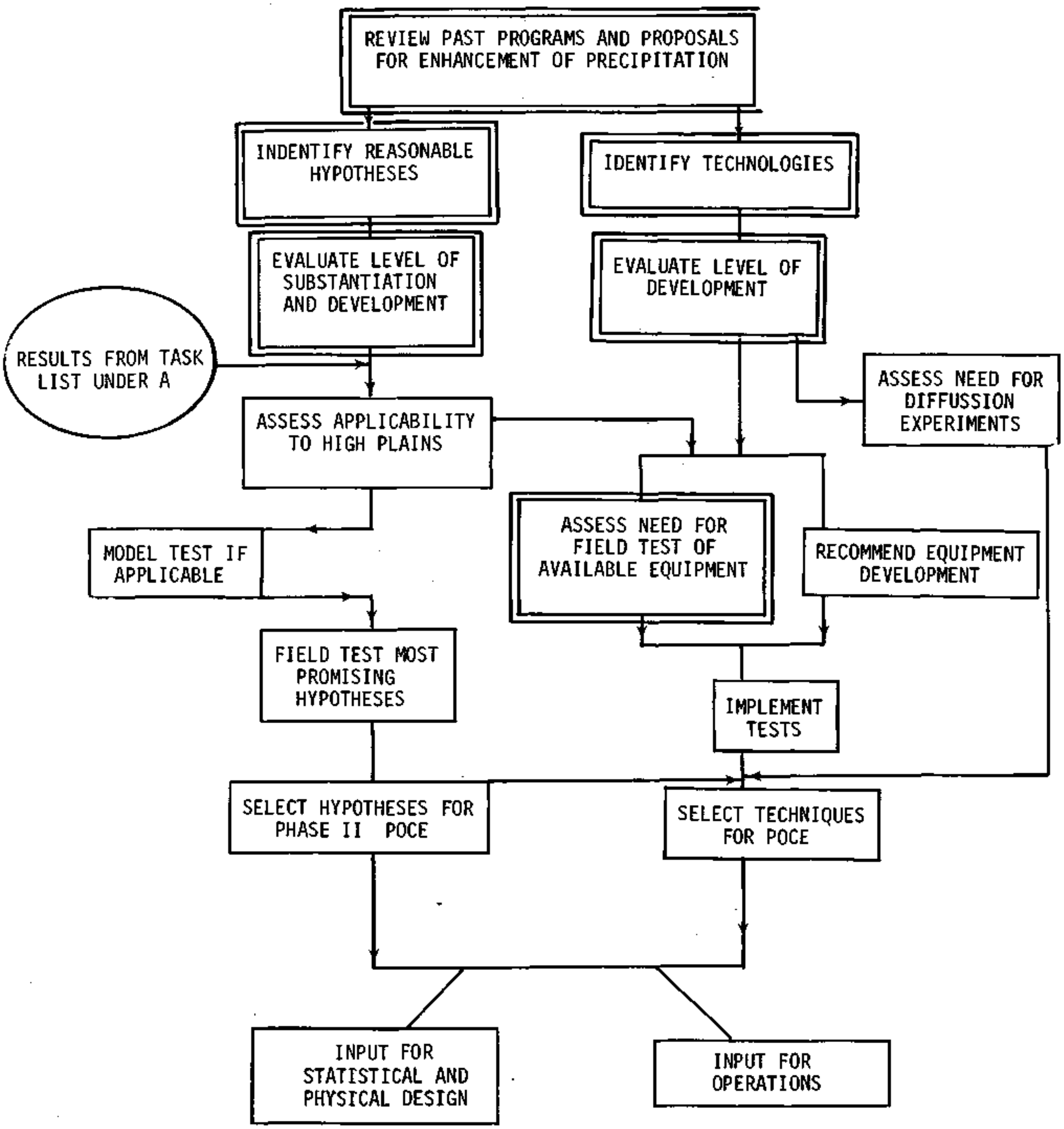
MODIFICATION AND HYPOTHESES AND TECHNOLOGIES

Figure 9. The assessment and decision factors leading to selection of modification hypotheses and techniques for the proof of concept experiment. Tasks undertaken by the design group at ISWS for design purposes are indicated by a double box.

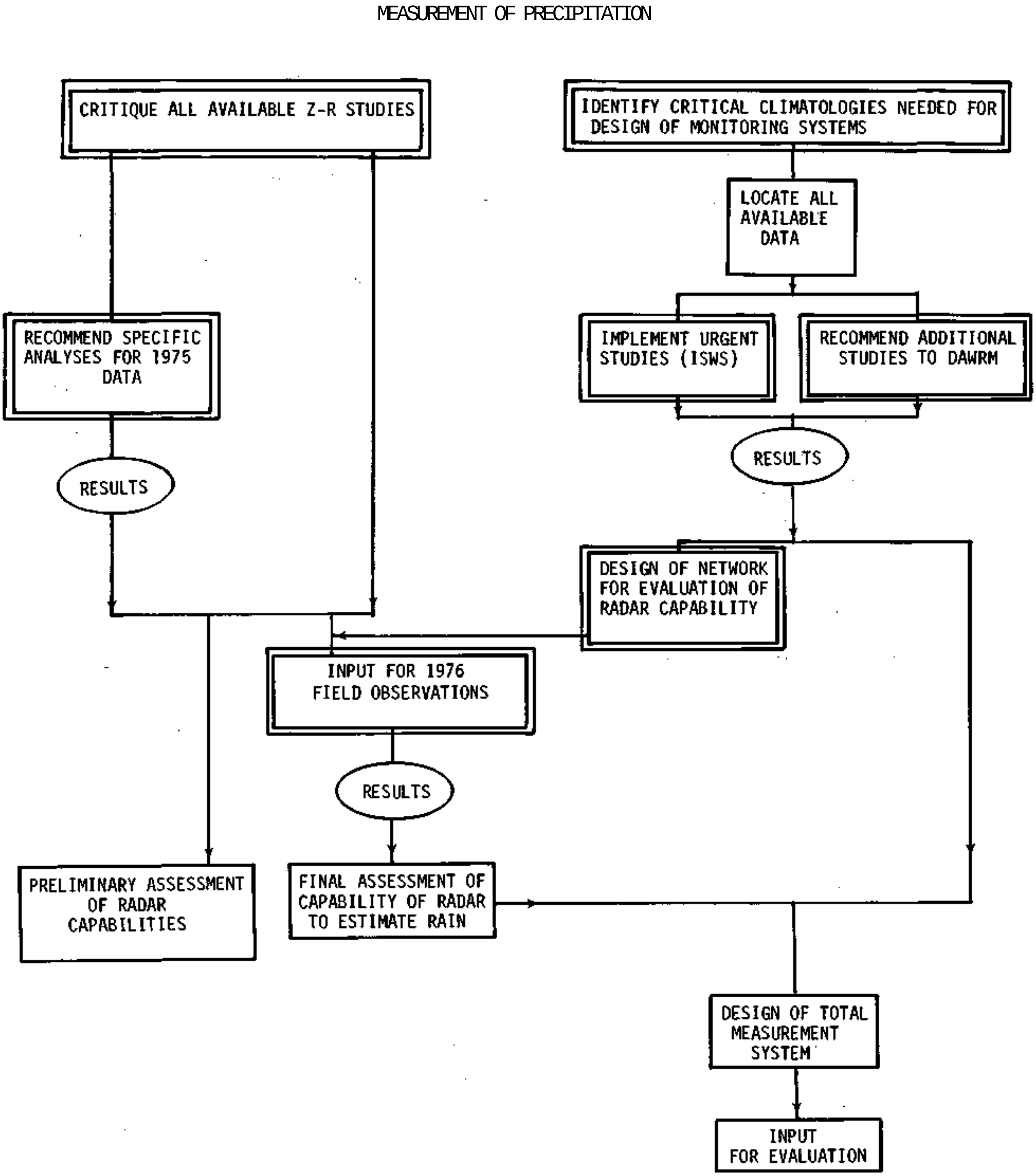

Figure 10. Studies which must be made for design of the system for measuring precipitation. Tasks undertaken by the design group at ISWS for design purposes are indicated by a double box.

IV. SEEDING EXPERIMENT - SINGLE CLOUD

A. General

The goal of the single cloud experiment is the removal of scientific uncertainties associated with the alteration of cloud and precipitation processes by selected modification techniques and the effect on the surface rainfall. Thus the objective is a scientific one -- to try to determine what effect treatment has had on the pertinent processes -- and a good portion of the burden of proof must rest on the evaluation of critical physical characteristics of the members of the seeded and unseeded populations prior to and subsequent to treatment.

Inadequate information on the characteristics of the clouds in the High Plains prevents definitive specification of many of the design aspects.- It is *essential* that research and analysis based on 1975 and 1976 HIPLEX field data and on other existing data banks from the High Plains be given *highest priority* so that the design can be formalized as soon as possible. Suggestions as to the types of analyses that are needed have been provided DAWRM periodically over the past year. These are reproduced in Appendix A.

Since the exploratory studies are not complete and input for the design stemming from the studies are not available, the design which follows is loosely formulated. It must be reviewed and revised in response to experience and to results from the exploratory studies. Some components of the experiment are given in considerable detail (e.g., operations) because they are not so specific to HIPLEX; others which are specific to HIPLEX and which depend on the results of the exploratory research are dealt with in a much more general manner.

The terms "semi-isolated single cloud", and "storm" are key descriptors of the phenomena which will be the subjects of the experiment. The following definitions have been tentatively adopted.

> DEFINITION: SEMI-ISOLATED SINGLE CLOUD - a complex of convective elements, visually distinct and separable from other complexes by distances ranging from one to several diameters.

This definition covers a broad spectrum of clouds which, in the Middle West, typically have diameters of 2 to 15 km, separations of 5 to 20 km, and depths ranging from 3-4 km to 10 km. A complex may consist of one large cloud containing one or more active cells, plus a number of small adjacent clouds or several active convective centers of equal but moderate size (Fig. lla-c). Frequently low-level stratocumulus or small cumuli form a nearly continuous layer around the base level of the large units. (Cumulus towers embedded in multiple layers, primarily altocumulus and altostratus (Fig. lid), are usually associated with synoptic systems in which large scale lifting plays an important role. These are not subjects for the single cloud seeding experiment. They will, however, be included in the area experiment and consequently should be the subjects of exploratory (non-seeded) study during the single cloud experiment.)

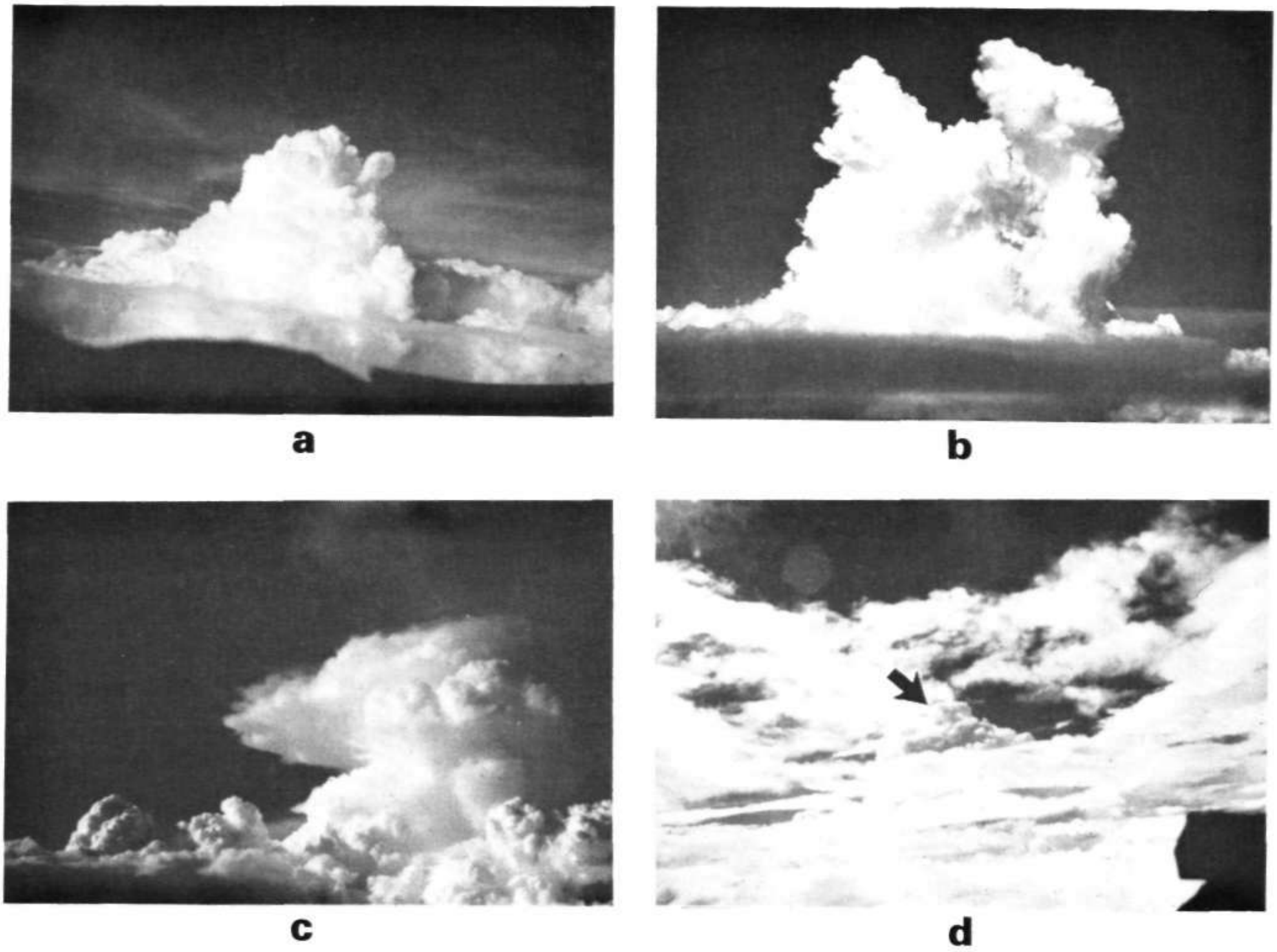

Figure 11. (a)-(c). Examples of Midwest semi-isolated single clouds, as defined for the single cloud experiment, (d). Cumulus congestus, developing into Cb calvus, embedded in extensive thick altocumulus layers, a cloud type <u>not</u> considered in the spectrum of semi-isolated single clouds. (All examples from southern Illinois and eastern Missouri).

> DEFINITION: STORM - a clearly identifiable cloud region encompassing one or more semi-isolated single clouds which throughout its history is clearly separable from all other such areas in space by a cloud-free area of at least 50 km and in time by at least 1 to 2 hours.

The clouds comprising the storm may be clustered, arrayed in lines, or scattered randomly within the region (Fig. 12). The areal extent and shape of the storm will vary with time as its member clouds develop, mature and die. The storm lifetime may be as short as a couple of hours — or as long as 15 or more hours -- but it is identifiable throughout and its motion (both from translation and propagation) is determinable.

These definitions are based largely on convective cloud and storm characteristics in the Middle West. *Whether or not they are appropriate for the northern, central and southern High Plains, must be determined as soon as possible from 1975 and 1976 field observations, and/or from data collected during earlier field programs in the High Plains. Typical cloud and storm dimensions and lifetimes should also be determined.*

B. Modification Hypothesis

1. Background

A number of experiments have been carried out over the past 25 years, the goals of which were to establish the capability of modifying cumulus cloud systems. Results reported in the literature have ranged from notable success in altering the physical characteristics of individual clouds and in increasing areal rainfall to lack of success on either count. in fact, the evidence to date indicates that the treatment can increase, decrease or have no effect on precipitation, depending on the existing meso- and larger-scale dynamics and resulting cloud conditions (National Academy of Sciences, 1966, 1973). An important target of the single cloud experiment — and of HIPLEX as a whole -- is to try to resolve this basic uncertainty in weather modification by identifying conditions which lead to such diverse outcomes of attempts to augment precipitation. To this end, the whole spectrum of clouds included in the definition of "single" cloud are considered suitable subjects, initially at least.

At the present, the only practical means of modifying the cloud and precipitation processes is by altering the size spectrum or phase of the cloud condensate through the manipulation of the natural populations of the condensation, freezing, and/or sublimation nuclei. There has been laboratory evidence that microphysical changes in the cloud condensate do probably occur approximately as predicted when nuclei are added or when naturally-occurring nuclei are activated. The mixed results from field experiments designed to investigate changes in cloud processes or in the production of rain illustrate the complexity of the total physical system. The poor predictability of the outcome of attempts to modify clouds and precipitation is symptomatic of the tremendous gaps in our understanding of cloud dynamical and microphysical processes and, most importantly, the interaction between the two.

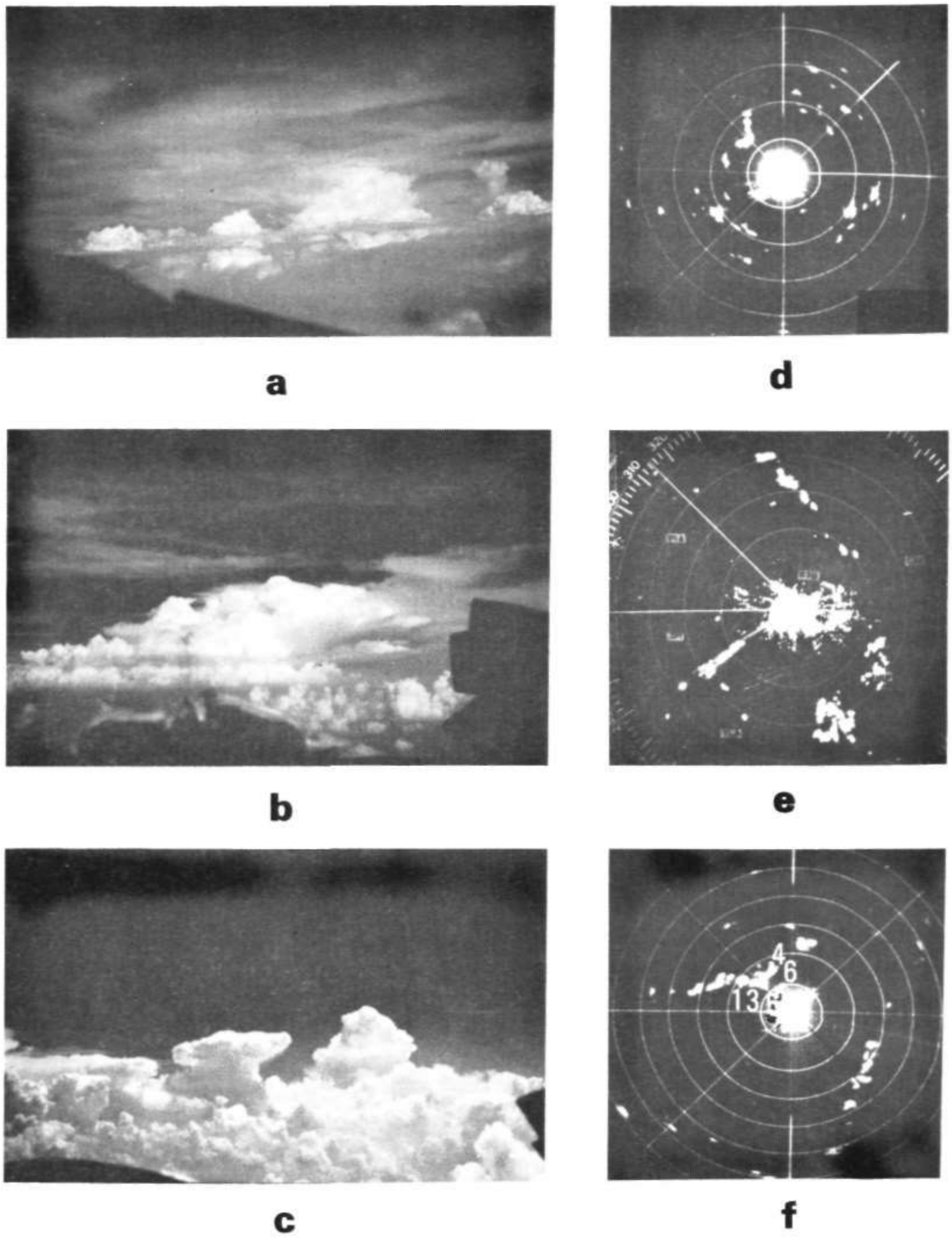

Figure 12. (a)-(c). Examples of storms in southern Illinois and eastern Missouri photographed at 16000 ft. (Only parts of storm areas shown).
(d)-(f). Radar scope photographs (PPI, 20 mi range markers) of storms in Illinois showing scattered echoes and echo clusters in unstable air masses in (d) and (e) resp.; and in (f), a line along a stationary front (northwest quadrant) and a second line of echoes in the warm air mass to the southeast.

2. Physical Basis for Development of Seeding Hypotheses

There have been several good expositions of the basis for cumulus cloud modification (e.g., Simpson and Dennis, 1974; Neiburger and Weickmann, 1974; Simpson, 1976) and it need not be repeated here. Only those aspects of the problem critical to the development of the design are repeated here, and these only in barest detail.

Most seeding hypotheses are based on the assumption that the production of precipitation from a suitable cloud (system) can be increased by the addition of appropriate nuclei. Productivity* can be Increased by an increase in the amount of vapor transported into the cloud system or by an increase in the efficiency** with which the cloud converts vapor to precipitation. It is important to realize that an increase in efficiency does not necessarily result in an increase in productivity. For example, if increased efficiency brought about by treatment is accompanied by a *decrease* in the active lifetime of the treated cloud so that, overall, less water vapor is processed, the productivity could conceivably be decreased. Conversely, if an increase in productivity is due to an increase in the amount of vapor drawn into the cloud, there may be no change, or even a decrease, in cloud efficiency.

In the following discussion, a distinction is made between initiation and augmentation of rain. The first term is used hereafter to indicate initiation and production of rain in clouds which would not rain otherwise; the second indicates an increase in the precipitation naturally produced by a cloud, even though this may be effected by the initiation of the precipitation process earlier than it would have naturally or in a region other than it would have naturally.

It is generally accepted that precipitation can develop in a cloud through the formation of large drops which subsequently collect smaller water droplets (warm rain or coalescence process) and/or through the conversion of supercooled cloud droplets into larger ice particles which subsequently scavenge water droplets and/or ice particles (cold rain or ice process). The basis for most modification hypotheses is the alteration of the time scale on which these processes operate, either by adding large condensation nuclei (CCN) to speed up the coalescence process or by adding artificial ice nuclei (IN) at an appropriate temperature level to start the cold rain process. In either case, the implicit assumption is that there is an inadequate number of appropriate nuclei naturally available for a productive rain process. The sequence of events following treatment with either large CCN or IN may take a number of paths (Braham, 1968) , most of

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*Productivity is defined as the total amount of precipitation produced at the ground by the cloud.

**Efficiency is defined as the ratio of precipitation produced to the amount of water vapor processed by the cloud system. A second definition frequently used is the ratio of precipitation produced to the amount of water vapor condensed. Since the water vapor drawn into the system is the basic "fuel", the overall cloud efficiency is given by the first definition.

which are poorly understood. This is particularly true of the feedback loops between the dynamics and microphysics which can play a deciding role in the ultimate outcome of the treatment. As a consequence, any number of physical hypotheses can be developed covering the chain between the introduction of additional nuclei into a cloud and subsequent precipitation at the ground.

Several methods have been suggested for the alteration of rain by manipulating the warm rain process. The one most generally accepted as realistic at this time is the introduction of large hygroscopic particles which serve as favored sites for droplet growth. The hypotheses that have been advanced are of two types.

(a) The large drops formed on the giant nuclei act as "collector" drops which scavenge the smaller ones and subsequently fall out as rain, with or without a multiplication of collector drops through the Langmuir chain reaction.

(b) The ice process is initiated early when the large drops formed on the added nuclei are transported to subzero temperatures, either because of early freezing or activation of natural ice nuclei as a consequence of increased supersaturations with respect to equilibrium over ice.

The most generally accepted -- and widely used — method for manipulating the ice process is the addition to the natural aerosol of artificial freezing or sublimation nuclei which are activated at relatively warm, but subzero, temperatures where the natural cloud condensate is dispersed in supercooled water particles. The hypotheses usually fall into the following two categories.

(a) Large solid particles develop as the frozen particles artificially produced grow rapidly in the supersaturated (relative to ice) environment at the expense of the liquid condensate, and subsequently act as collectors of cloud droplets and small crystals (static seeding).

(b) The updraft is accelerated as a consequence of the heat realized in the rapid conversion of all liquid condensate and supersaturated vapor into ice, leading to an increase in the low level moisture which flows into the cloud (dynamic seeding).

Some dynamic effects are likely to accompany the microphysical changes in type (b) "hygroscopic" seeding and type (a) "ice" seeding. The dynamic consequences of the type (a) hygroscopic seeding are more difficult to predict since possible increase in net buoyancy in the upper part of the updraft (due to large drop sedimentation and reduction of liquid water) may be accompanied by significant decrease in the net buoyancy of the lower updraft regions. In Midwest clouds in which the coalescence process is very active, substantial water loading has been observed in updrafts in the upper half to upper third of the cloud, and three to four kilometers above cloud base (Ackerman, 1974).

The recommended design of the single cloud seeding experiment is based only on the manipulation of the ice process. The decision to confine the experiment to ice seeding was based on a number of considerations. Foremost among these was the principal charge from DAWRM, to wit, to design a single cloud experiment from pre-experimental studies through to the proof of concept stage, which included consideration of production of rain on the ground. This required that the number of hypotheses be limited if the experiment is to be of reasonable length (e.g., about 5 years).

Given this requirement, the hierarchy of hypotheses were screened for the following factors:

suitability for the natural cloud populations

accumulated body of knowledge regarding techniques

accumulated body of knowledge regarding the outcome of modification attempts, based on operational and experimental programs

logistic requirements

Hypotheses based on modification of the warm rain process were considered and rejected. Theoretically there seems to be little question that the introduction of large CCN near the base of a cloud with base temperatures above freezing will result in the development of precipitation-size drops earlier than would occur naturally, if such particles are in short supply in the natural atmospheric state. It is even likely that under certain circumstances it may also cause some precipitation to fall from clouds that would not produce rain otherwise. However, the likelihood of significant augmentation of rain from clouds which would rain naturally is, at this time, highly speculative. The early formation of large drops and subsequent water loading in the lower reaches of the cloud can lead to early deterioration of the updraft there, resulting in a decrease of total inflow of low level moist air. Thus, though the efficiency might be increased, the productivity could be decreased. Although much is to be learned, it appears, based on midwestern data (in lieu of data for the Great Plains), that an overall economic benefit will depend on augmentation, since the amount of increased rainfall from initiation alone may be quite small.

Significant precipitation increases from seeding with hygroscopic nuclei requires clouds three or more kilometers deep. In most of the High Plains, clouds of this depth have reached levels where the ice process could be initiated through treatment with appropriate seeding materials. Logistically, ice-nuclei seeding is simpler because the existing seeding technology for hygroscopic nuclei requires larger aircraft or frequent reloading. Moreover the accumulated body of knowledge regarding ice seeding is far greater than for hygroscopic seeding. Thus, on all four counts listed above, ice seeding is favored for HIPLEX.*

*One may speculate that the early development of a downdraft in a critical region could cause a group of relatively small clouds to develop into a more organized cloud area which would be a better producer of precipitation. However this hypothesis is highly speculative and requires a great deal of theoretical and empirical research. Exploratory research on natural situations of this kind would be worthwhile provided it does not interfere, <u>in any way</u>, with the execution of the design of the single cloud experiment as developed here.

As indicated earlier ice seeding can work in two ways. Light to moderate seeding rates (static seeding) can lead to the production of a relatively small number of ice particles (e.g., 1 to 10 crystals/liter at -10°C) which would then grow rapidly by sublimation at the expense of the smaller drops to a 100-y precipitation "embryo" in 3 to 5 minutes. These embryos then collect smaller crystals and small supercooled liquid drops lying in their fall paths, and thus grow into particles large enough to precipitate. The second method involves massive seeding to produce over 100 crystals/liter throughout the supercooled cloud, thus releasing large amounts of latent heat. This leads to increased buoyancy, an acceleration of the updraft, greater cloud growth, increased inflow of water vapor, and greater precipitation. This is known as dynamic seeding. (Of course even light seeding results in dynamic enhancement, though at a much lesser rate.)

The experiences of at least two experimenters in the High Plains have led them to conclude that the lower seeding rates will probably be more suitable for the High Plains, either because environmental conditions are not favorable for significant artificially-stimulated cloud growth (Texas, Smith, et al. ,1974) or because of the high probability of overseeding (North Dakota, Dennis, et al. ,1974). Seeding "climatologies" also suggest that the opportunities for dynamic seeding are fewer than one would desire. However, these seeding climatologies, based on 1-D steady state model estimates, should be re-calculated using only those days on which synoptic conditions favor development of convective clouds of some significant size. The general climatologies may be so diluted with unfavorable, large scale dynamic situations as to obscure the true potential for dynamic seeding.

In the absence of the appropriate climatologies and, equally important, of knowledge of the amount of supercooled liquid water at the -5 to -15°C levels, which to a large extent determines the potential for dynamic enhancement with massive seeding, the recommendations of Smith and Dennis have been tentatively accepted as one hypothesis that should be tested further in the High Plains. Therefore *an experiment in which light to moderate seeding rates are used is recommended.* However, *a second hypothesis based upon massive seeding for major dynamic enhancement is also proposed for testing, tentatively at least,* since it may be the more productive method. Environmental thermodynamic data and cloud measurements in the pre-POCE period should be analyzed to determine if dynamic seeding may be a fruitful approach, and if so, it should be included in the seeding experiment.

3. Initial Conditions - Cloud Characteristics

Virtually all of the experimental and operational seeding programs have pointed out two very important facts: 1) there is a range of general environmental conditions which are favorable for the development of clouds suitable for treatment (in this case for convective clouds which at least have the potential for precipitation development), and 2) given large-scale conditions favorable for cloud development, the outcome apparently depends on the characteristics of the clouds or cloud arrays which are to be treated and on the immediate environment. A major contribution to the removal of the uncertainties associated with current cloud seeding operations will be made if the joint conditions of the critical parameters are identified for the three possible seeding outcomes (no effect, negative effect, or positive effect) for each of the synoptic conditions which favor convective precipitation.

a. *Cloud Characteristics*

Background information on the characteristics of the growing-season clouds in the High Plains is still sketchy. The following features of convective clouds which are significant for hypothesis formulation have been distilled from information, in many instances fragmentary, primarily from the preliminary 1975 field analyses available in reports from Bureau of Reclamation field groups and contractors. Other sources which have been relied upon heavily are the South and North Dakota projects, the Kancup project, the San Angelo experiment and the Big Spring operations. The cloud characteristics listed below should be updated as studies underway are completed and as additional observations from the field program become available.

(a) Cloud base temperatures average about 9°C in the northern plains, 11 or 12°C in the Central Plains and about 14°C in the Southern Plains, with a day-to-day variation resulting in a range of about 10°C in each area.

(b) There are no systematic differences in the characteristics of the droplet spectra at cloud base in the three areas, although day-to-day variations at any one location are significant. Moreover, precipitation embryos are found in significant concentrations at cloud base in all three areas. (Data are sparse and must be substantiated with additional observations.)

(c) Updrafts at cloud base range from 2 to 13 mps but are typically 5 mps; stronger updrafts are usually associated with larger updraft diameters and longer updraft durations. Typically, updrafts have diameters of 2 to 2.5 km and durations of 10 minutes. (Data are sparse and conclusions need to be verified.)

(d) The coalescence process is active,at least part of the time, in producing some of the initial precipitation-size drops. However, clouds deep enough for production of significant amounts of precipitation have usually penetrated well into the region of subzero temperatures.

In order to develop the seeding hypotheses to be used in HIPLEX it has been necessary to consider a conceptual model of the convective complexes which will be the sample units. Knowledge of the internal structure of convective clouds is sparse, not only for the High Plains but for all areas in the United States. The conceptual model described below is based on information consolidated from all sources, but leans most heavily on data from the High Plains. It must be evaluated continuously as the radar and airplane measurements accumulate and should be modified as necessary. Large and meso-scale conditions have been assumed favorable for development of such clouds.

b. *Conceptual Model*

As specified in the definition adopted for single cloud (Section IV.A), the subjects (sampling units) are actually cloud complexes which may be (1) a close cluster of several cumulus congestus clouds of moderate size or (2) a small cumulonimbus around which are clustered a number of satellite clouds. (At least in southeastern U. S. and the Mississippi Valley, the former is often the precursor of the latter, that is, a group of cumulus congestus often organizes into a small cumulonimbus.) Since ice seeding is the basic approach to be used in the experiment, the clouds of interest must extend beyond the freezing level. This implies cloud depths of 3 to 4 km in the northern plains and 4-5 km in the southern plains.

In-cloud observations have usually indicated a strongly turbulent structure, which manifests itself in a high variability of all cloud parameters in space. Although smooth updrafts are often reported, this observation must be viewed in light of the response of the sensor, usually the airplane itself, and may or may not be a true characteristic of the updraft. Warner's (1970) analysis of the velocity structure in small- to moderate-sized, warm-based convective clouds suggests that the roots of the updraft are composed of a number of smaller thermals, which maintain their identity close to the cloud base but which organize and merge further up in the cloud. The organization tends to break down again near the top. This model of the dynamic structure is tentatively accepted for the smaller clouds in the High Plains, although it is recognized that, in high-based clouds, organization of the updraft may occur in the sub-cloud layer. The dominant cloud elements in the complex will have the more organized updraft systems both at cloud base and in the middle levels, that is, the updraft elements will be larger in dimension and there will be fewer of them.

There have been measurements in High Plains storms that suggest that the energy in <u>small-scale</u> turbulence increases with height. However most of these utilize an instrument that assumes an inertial subrange in an arbitrary frequency band in which the -5/3 law applies. The validity of these assumptions in highly convective conditions has yet to be tested. In Ohio thunderstorms, peak gust velocities were roughly the same at all levels between 2 and 8 km (Byers and Braham, 1949), suggesting more homogeneous turbulence conditions with height.

In addition to this very elementary concept of the dynamic structure of the cloud, the following conditions are assumed at the level at which the artificial ice nuclei are usually activated (-5 to -15°C): (a) the condensate in the active updraft regions will be predominantly, if not entirely, liquid and largely in small cloud droplets due to the lack of natural ice nuclei active at temperatures above -15°C; and (b) although there may be local areas of high liquid-water content, the concentration of the condensate in the active updraft region will generally average less than the adiabatic value, probably no more than 2 to 3 gm/m^3 in the northern plains, and 3 to 4 gm/m^3 in the southern plains.

Again it is stressed that existing data sets must be studied and new measurements made to check on the validity of these features for the high-based clouds of the semi-arid High Plains. It is *essential* that the following characteristics of the cloud condensate be determined by measurement: (a) in the seeding region, the amount of condensate and the fractions incloud droplets, precipitation and embryonic drops, and in ice particles, and (b) at cloud base, the droplet concentration and, preferably, also the spectrum. The amount and character of cloud condensate not only determines the potential for dynamic enhancement of the updraft, but also is important in determining the need for artificial nuclei and the possibility of overseeding. The relative frequencies of organized updrafts of a significant size, and of the less organized arrays of updrafts which, in total, extend over 2 or 3 km but which individually are no more than a few hundreds of meters across, also should be established early in the exploratory work. This has more than passing interest, since the transport and diffusion of the seeding material could be vastly different in smooth, organized updrafts as opposed to the more turbulent arrays.

4. Hypothesized Changes in Clouds and Precipitation Due to Seeding

The assumption was made above that naturally occurring ice nuclei active at temperatures warmer than -15 to -20°C are so few in number as to be negligible. Thus natural glaciation would not occur until the cloud penetrates above these temperature levels. Introduction of suitable particles (e.g., silver iodide) will cause ice to form at warmer temperatures.

Freezing in the free atmosphere is very complex and there are many questions remaining regarding the details of the process. Currently several types of ice nucleation are hypothesized as occurring:

(a) Freezing or immersion nucleation in which crystallization occurs around an active nucleus which is immersed in the drop.

(b) Contact nucleation in which the active nucleus impinges on the surface of the supercooled water drop and freezing takes place rapidly (within a few seconds) on the dry surface.

(c) Sorption nucleation in which water molecules are absorbed on a nucleus and freezing then occurs (vapor→liquid→solid transition).

(d) Deposition nucleation in which ice crystals are formed directly on the active nucleus from the vapor (vapor→solid transition).

The last three can occur only if the nucleus exists in its dry state at subzero temperatures; in immersion freezing, the nucleus can become resident in the drop below the freezing level, provided the residence time is not sufficient to deactivate the nucleus through etching of the active sites.

The preferred mode of nucleation by AgI is also unknown. Since it appears that the most effective particle size and the temperature of activation differ for the various modes (Young, 1974; National Academy of Sciences, 1973), this is an area of considerable importance.

a. *Light to Moderate Seeding - Static Seeding and Formation of a Precipitation Screen*

It is assumed that activation can be of all of the above types, and that each of the three modes of nucleation will act over some length of time. Thus, the transformation from liquid to ice will not be immediate but will occur over the temperature range of -15 to -20°C. Once the conversion from water to ice is underway, it will include whatever natural ice multiplication processes might be active at the particular temperature, supersaturation and with the existing condensate. It is hypothesized that the combination of the various nucleation modes, the natural multiplication processes, and the deactivation of the artificial nuclei will result in a transformation of the available water to ice between the -5°C and the -15°C levels such that there is a roughly exponential increase with height in the fraction of total condensate in ice.

The link between the microphysical changes and the cloud dynamics is a most crucial aspect of the modification efforts, but it is also, by far, the least understood. Consequently what follows as a consequence of the early initiation of the ice phase is, in some respects, conjecture. The ice particles formed in the layer between -5 and -15°C due to the seeding will initially be small crystals, which will grow quite rapidly at the expense of the liquid drops. Since they develop differential fall rates relative to the small drops, they will collect them and become rimed, leading eventually to a predominant ice form of small pellets, or graupel. It is hypothesized that in the first few minutes the sedimentation rate of the crystals will be slow enough and that the contribution to a deceleration of the updraft due to water loading is counteracted by the added buoyancy realized from the latent heat released in the freezing. As it continues to rise the air will be relieved of its water load and the upper portion of the updraft will tend to accelerate somewhat. At the very least the updraft will be sustained, if not accelerated, in the upper portion of the cloud. Thus it is hypothesized that the cloud is likely to reach, and probably exceed, the height it would have naturally. Because the ice crystals form in the warmer part of the cloud, crystal aggregates are more likely to form and this, in conjunction with sustained or increased updraft speeds, will result in larger precipitation particles. This has two favorable effects: improved collection of cloud water as the particles fall through the lower part of the cloud and greater likelihood of reaching the ground before complete evaporation.

The effect of the early initiation of large particles and consequently of water loading on the total lifetime of the cloud area is unknown. It was hypothesized above that the release of latent heat of freezing relatively low in the cloud will offset the negative buoyancy introduced by water loading, and that the reduction of water load in the uppermost portion of the cloud would have a positive effect on growth. Seeding results from some seeding experiments suggest that even with moderate seeding, the cloud experiences dynamic enhancement, sometimes manifested as horizontal expansion rather than vertical growth. This could be due to the involvement of surrounding air in cloud development, to mergers with adjacent turrets, and/or to the development of new cells. Moreover, evidence has been emerging from tracer and seeding experiments that there is a transfer of material between cells (Semonin, 1972; Summers, 1972). Therefore artificial ice nuclei released into one updraft in a conglomerate may enter an adjacent cell, or may be introduced into a new updraft or new cell, and, if still active, could modify the precipitation process. A third effect, also dynamic, is associated with the development of a downdraft as the rain starts. If a significant downdraft is developed below cloud base it is compensated for by an upward acceleration of the air surrounding it, and possibly the development of new updrafts. This mechanism has long been proposed an important one in the development of organized thunderstorms. It is even more critical to the positive outcome of seeding if, due to the early initiation of precipitation, the duration of the seeded updraft is decreased.

b. *Massive Seeding - Dynamic Enhancement*

Dynamic seeding is presented as a second hypothesis to be tested, if exploratory studies indicate that appropriate cloud and environmental conditions occur with sufficient frequency in the High Plains. It has been shown that, in humid air masses, massive seeding can cause significant enhancement of the cloud dynamics, resulting in increased flow of moisture through the cloud system, and increased production of precipitation from that system (Simpson, et al., 1973).

For dynamic seeding to be effective, a number of conditions need to be met. First of all, in the temperature range of interest, the supercooled liquid water content must be high enough for significant amounts of heat to be released as it is converted from water drops to ice particles. Secondly, the artificial nuclei must be distributed throughout the active cloud volume in sufficiently high concentration and in a sufficiently short time so as to glaciate enough of the supercooled water to significantly increase the buoyancy. Thirdly, the environmental conditions limiting natural cloud growth must not be so unfavorable that they cannot be overcome. Optimum results occur when explosive cloud growth occurs as the cloud breaks through a stable layer or a shallow dry layer. However, if either of these are too strong or deep or if widespread divergence dominates, the induced growth may be negligible. The seeding may then cause a decrease in the precipitation since the increased vertical velocities, accompanied by essentially no increase in depth, results in a decrease in the time available for the microphysical processes to operate.

Given that the above conditions are satisfied, massive seeding of active cloud areas can increase the production of precipitation because the greater cloud depths provide more time for the microphysical mechanisms to operate and/or because the enhanced updraft causes an additional amount of the moisture to be drawn into the cloud from its surroundings. Although both may be factors, it is the opinion of the Florida group, who have used this mode of seeding most extensively and successfully, that it is the latter that is the dominant one (Woodley and Sax, 1976). If this is so, then the level from which this air is drawn is important, particularly in the High Plains. Although figures are not now readily available for days favorable for cloud development, in general the air in the mid-levels for clouds in the northern and central plains tends to be very dry and would supply relatively little vapor if brought into the system. For significant increase in the vapor processed, it is necessary to hypothesize that the enhanced vertical motion results in moisture convergence below the cloud and/or in the vicinity of the cloud base (perhaps because of local reduction of pressure) and increased inflow of moist lower tropospheric air into the cloud system. The net effect is increased organization of the updraft near the cloud base, and in the dimension of the primary input scale of thermal energy as well as the areal extent of the updraft, and consequently the width of the cloud.

A second, highly important, effect of the dynamic enhancement of a single cloud has been hypothesized in circumstances where the seeded cloud is a member of a group. This is associated with the 'merging' of unseeded cells or clouds with the seeded cell, to form a larger system with an overall longer lasting meso-scale inflow system. Merging has been observed to occur naturally in the atmosphere under certain conditions when one or two clouds in a group become large enough to cause a modification in the ambient flow field. If the dynamic enhancement of the seeded cloud is sufficient to cause it to pass into a larger class of clouds than it would have been normally, the outcome of the treatment may extend much beyond that which can be expected from the treated cloud alone since larger systems are known to be better producers of precipitation at the ground. *Thus, the potential of dynamic seeding as an effective means of augmenting High Plains precipitation should be carefully investigated and included in the experiment if the results warrant it.*

5. Quantitative Aspects of Seeding Technology

Silver iodide (Agl) remains the favored material for artificial ice nucleation. A number of other nucleating materials have been suggested and tested from time to time. However the technology of these needs much development and there is little accumulated knowledge as to their effects. In addition, techniques for cooling the air to the point of homogeneous nucleation have been proposed and tested. There are both significant advantages and disadvantages to these proposals, v/hether dry ice, liquid air or other techniques are used. Among the advantages is the total lack of any nucleating substance which might be suspected of creating "holdover" effects or entering into precipitation systems not involved in the experiment. It would also avoid all questions of environmental effects due to accumulation of nucleating agents in streams, on plants, etc. The mode of action of these nucleating substances is qualitatively if not quantitatively understood and many of the uncertainties associated with other types of ice nuclei are avoided. Their use requires, however, direct injection into the supercooled region of large masses of material. The problem of the diffusion of the effect through the desired volume remains, with the difference that this comes about primarily through the diffusion of ice crystals. Another disadvantage may lie in logistics, where the technique requires heavy materials or equipment. Early Australian experimenters with this approach using dry ice concluded that, despite promising results, the economic practicality was doubtful (Smith, 1974).

The technology, advantages and disadvantages of cooling techniques and of nucleating materials other than Agl merit exploration. However, in line with the factors to be considered in the design given in IV.B.2, it is recommended that Agl be a primary (if not only) nucleating agent used in the High Plains experiment.

There are many uncertainties concerning the fate of the Agl once released into the atmosphere: the degree to which it is dispersed through the cloud; the ice nucleation mechanism itself, both natural and artificial; deactivation of the Agl nuclei; coagulation of the nuclei at the time it is released, etc. These make it difficult to specify the exact amounts of reagent to be employed. Treatments are often specified only in gross terms; such terms as "light", "moderate", and "heavy" or "massive" are generally accepted and the amounts of material used by various operators and experimenters cover a wide range. In terms of the number of ice crystals desired in the precipitation-development region, light to moderate seeding is expected to produce 1.0 to 10.0 ice crystals per liter at -10°C, heavy or massive seeding, hundreds of crystals per liter at -10°C.

A review of the techniques employed in various projects in the High Plains is given in Appendix D. Those that appear most promising for HIPLEX are discussed below.

Material can be delivered into the updraft at cloud base, from some general level within the cloud or by dropping into the cloud from above. The advantages of cloud base injection are the ability to identify the updraft region and to loiter with the aircraft in that region. However if there are several cells and some smaller clouds surrounding the main complex, so that visibility is restricted, there may be considerable uncertainty as to whether the appropriate turret or cell has been treated. The "on top" approach has the advantage that the active growing cells usually are easy to identify and it is possible to return to them quickly. However, once the flares are released there is some uncertainty about what happens to them (e.g., they may not remain in the updraft if it slopes in the vertical) and about the nuclei they produce. Penetrating the cloud interior with the aircraft and releasing flares has the advantage of choice of temperature level at which to release. The great disadvantage is that the location relative to the updraft is not well known and loitering in the cloud updraft is nearly impossible. While the dispersion of the nuclei from the level of release is always in question, cloud base release would seem to be the most favorable situation in this regard since it provides more time for natural diffusion mechanisms to act.

For light to moderate seeding, the cloud base approach appears overall the best. However for massive seeding, leading to rapid glaciation and dynamic enhancement of the cloud, seeding directly into the turret either just below or immediately above the summit is probably the most effective since the phase conversion can be initiated through a deeper layer in a shorter period of time.

Very heavy seeding is accomplished best with flares which contain less than 100 g Agl each but can be dropped in large numbers so that the total treatment may be from 0.5 to over 1.0 kg per turret. Each of these flares burns for periods of up to a minute while falling through the cloud. Light to moderate seeding can be accomplished by use of small numbers of such flares, or with wing-mounted flares or burners. The burners consume a solution which releases several hundred (typically 300-600) grams of Agl per hour (5 to 10 g/min). They can be turned on and off to control the dosage. Wing-mounted flares typically contain 25 or more (as much as 120) g of Agl and during the burn release Agl at rates of about 5 to 10 g/m?n. They typically burn for 5 minutes. More than one flare (or burner) can be ignited simultaneously. Use of the wing-mounted devices requires that the aircraft loiter in the seeding area for some minutes.

Of the sources of Agl nuclei, the Agl-NH_4l-complex solution appears best because of the desirable properties claimed for the nuclei it produces; they survive the deactivation processes which can otherwise be severe when they are injected at cloud base or within the warm part of the cloud. More than one burner can be mounted on the aircraft and dummy solutions and burners can be provided for randomization purposes. The Agl-NH_4l-complex solution yields on combustion 10^{12} nuclei/gm Agl, active at -5°C (Blair, et al., 1973).

Prior to a final decision on the technique to be used in the single cloud experiment itself, exploratory studies should be carried out to investigate at least some of the uncertainties mentioned above. Of course the output of the burners or flares should be laboratory tested for production of nuclei but perhaps the most critical problem relates to the dispersion of the material. It is important that a significant fraction of the updraft contain active Agl nuclei in the layer between -5 and -15C levels. In order to determine how well this requirement is satisfied, the following studies are recommended during the exploratory phases of the experiment, more or less in priority order:

(a) Bulk condensate should be collected in the region between -5 to -15°C for silver analysis. This will not give any definitive information on whether the Agl had been active in the precipitation process. However it will provide information as to whether the material is well dispersed (normal to the seeding path) since, if it remains as a narrow strip with little broadening, the likelihood of intercepting it is low and silver would be found on few traverses. Of course extreme care has to be taken to prevent contamination.

(b) Experiments designed to investigate the possibility of increasing the width of the seeding trail should be carried out. One method would be to increase the turbulence around the seeding device by flying the airplane in an untrimmed configuration (e.g., nose high, flaps down, etc.) and/or adding "spoilers" to burners.

(c) Since the basic premise is that seeding with Agi particles will cause ice crystals to form, this is an obvious point to check. Thus it is recommended that measurements be made to detect the existence of ice particles and preferably the form and concentrations also in the region between -10 and -15C. (Crystal measurement is also recommended for evaluation throughout the experiment.) Instrumentation for accomplishing these measurements exists in several forms (replicators, optical devices, cloud cameras) and the type chosen should be capable of revealing all sizes and shapes of crystals.

(d) Estimates of diffusion of particulates are difficult to make, even in less complicated atmospheric systems. Nevertheless, they may serve to provide "ball park" figures. To do this, appropriate turbulence measurements should be made both at cloud base and at mid-levels.

All of the above should be carried out for at least three or four seeding rates, and for seeding into the updraft at cloud base and into the top of the developing turret. If seeding at mid-cloud levels appears feasible, trials should also be carried out at these levels.

6. Refinement of Hypothesis by Observations and Model Experiments

In developing the general hypotheses for HIPLEX above, the effects from seeding with artificial nuclei were traced through the modifications expected in microphysical and dynamical characteristics of the cloud which would lead to increases in surface rainfall, with the assumption that environmental conditions were favorable. In fact, however, the potential for both natural and modified cloud rainfall is determined in large measure by meso- and larger-scale processes and by the nearby environmental conditions which are a product of both these and of the local micro- and convective-scale processes. The various processes involved in the production of convective precipitation and their interactions are so complex and so incompletely understood that it is difficult to predict the outcome of seeding.

The hypothesized sequences of events given in Section IV.B.4 were based on scientific deduction, utilizing all available evidence. It is desirable to pre-test, correct and refine some of the anticipated changes into testable hypotheses by observations of naturally occurring phenomena and by computer experiments utilizing appropriate numerical cloud models and environmental and cloud conditions observed in the High Plains.

The critical, but measureable, elements in the chain of events hypothesized to occur as a consequence of seeding, and the assumptions that are made in developing the seeding hypotheses are summarized below. This section deals only with refinement of hypotheses; observations and model computations needed for evaluation are given in Section IV.C.3.

For both seeding hypotheses, measurements are needed in a significant number of clouds (50 to 100, depending on the local natural variability) to determine the appropriateness of the assumptions made in developing the general hypotheses, and the critical initial conditions. The following measurements should be made in clouds which meet the suitability criteria, i.e., actively growing, identifiable elements with tops penetrating the freezing level but below the -15 to -20°C levels. They must be accompanied by detailed analysis of the larger scale synoptic and sub-synoptic conditions.

In the cloud between the -5 and -10°C temperature levels

- Concentration of ice particles (all sizes) in the updraft.

Updraft speed and dimension.

- Total liquid-water content and its partition between cloud and precipitation particles, or, if possible, drop spectra.

At cloud base

Updraft speed and dimension

- Temperature and height of base

Droplet spectrum in updraft
Existance and strength of downdraft and rain shaft

In clear air

Nearby environmental soundings supplemented with clear-air thermodynamic measurements in the cloud region.
Concentrations of ice nuclei active at several supersaturations (temperatures).

Based on these measurements, and variable seeding rates (including no seeding), model computations designed to test the hypothesized changes listed below should be carried out *to the extent possible* at the present state-of-the-art. The objective of the model experiments is to test the resonableness of the predicted events, to check on the sign of the predicted change (i.e., increase, decrease, or none) and, where possible, to predict the magnitude of the changes as a function of initial cloud conditions.

In addition, the measurements from a rarrge of cloud types should be carefully analyzed to determine natural behavior for various environmental conditions and natural glaciation temperatures.

a. Light to Moderate Seeding: Qualitative predictions to be tested.

(1) Conversion of water to ice starts at -5°C and is completed below the -20°C level. The fraction of condensate in solid phase increases logarithmically with height.

(2) Form and size of artificially-produced ice particles are clumped crystals and subsequently graupel.

(3) There is essentially no change in the net buoyancy at the levels where the water to solid transition takes place, but there is an increase in temperature.

(4) There is no significant change in the updraft speed at the levels at which most of the freezing takes place; above -15°C an acceleration in the updraft may occur.

(5) Maximum height reached by the seeded tower will be greater but not by a large amount.

(6) There is no significant decrease in the duration of the seeded updraft at the cloud base.

(7) The cloud expands horizontally resulting in areally more extensive updrafts. New cells may develop, and if so the total duration of updrafts will be greater than if seeding had not occurred.

(8) Precipitation particles at cloud base will be larger and rainfall rate at ground will be greater.

(9) The rain efficiency will be greater, with some increase in productivity.

b. Dynamic Seeding: Qualitative predictions to be tested.

(1) Conversion of water to ice is very rapid throughout the region from -5 to -20°C.

(2) Ice form is more likely to be crystals or snowflakes; with very high initial liquid water contents, the precipitation particle (or embryo) may be "mushy" ice.

(3) There will be an increase in temperature and net buoyancy throughout the region of freezing.

(4) The updraft speed will increase throughout the sub-zero region and probably below.

(5) In the absence of a strong synoptic-scale elevated inversion the top will grow significantly beyond what it would naturally.

(6) A region of moisture convergence will develop just below the cloud and there will be an increase in the flow of moisture through the cloud base.

(7) The horizontal extent of the active cloud will increase and the updraft will increase in diameter.

(8) If the seeded cloud is one of a family, a merger with an adjacent cloud is likely to occur.

(9) There will be an increase in productivity (i.e., in the total surface rainfall) but not necessarily in precipitation efficiency.

(10) The rain intensity (rain/time/unit area) will not change significantly but the average rainfall (rainfall/total duration of rain) will increase.

(11) The precipitation spectrum at cloud base will not be changed significantly.

A whole hierarchy of cloud models have been developed over the past 10 years. However it is recognized that some of the factors listed above are beyond the scope of the most sophisticated of today's working models and will have to remain as stated. In implementing these computer experiments, a careful selection should be made of the most appropriate model to use, so that the results will not only be reasonable, but will provide increased understanding of the main process involved. When feasible, the output of a simpler model can be used as a guide for parameterizations in a more sophisticated one.

The one-dimensional, steady state model is of very limited use for hypothesis testing except for determining the climatological potential for dynamic seeding. The one-dimensional time dependent models with detailed microphysics can be used in testing many of the hypothesized changes. However the 2-D models are needed for checking on most of the dynamical consequences which are suggested. Since the cost of running the 2-D models with detailed microphysics is very high, it is suggested that the possibility of using parameterized microphysics based on the results of the 1-D models with complete microphysics be investigated.

The purpose of these computer tests is three-fold: to provide some theoretical basis for the proposed changes; to provide an identification of the initial conditions which can lead to different outcomes; and to provide quantitative estimates of the magnitudes of the changes that occur. This is a major order, and the results must be viewed as estimates since most of the models have had very limited evaluation of their ability to predict what actually occurs in nature.

C. Statistical Design and Evaluation

1. Randomization Scheme for the Seeding Experiment

An essential feature of the design of an experimental program in cloud seeding is an appropriate method for randomizing the treatment*. The most commonly used scheme in recent years has been the random-experimental design, which involves the randomization of the experimental unit (usually day or sub-set of days) over a single target area into seeded and non-seeded units. The evaluation is usually based on the daily rainfall or hailfall averaged over the target area. In view of the objective of the single cloud experiment, namely the reduction of the scientific uncertainty, use of areal rainfall is not appropriate for evaluation in Phase 2.

In the discussion below, the terms "single cloud" and "storm" are used according to the definitions given in Section IV.A. Each cloud produces an identifiable rain "cell" at the ground (if it precipitates) but neither the rain nor the cloud development can be considered as entirely free of the influence of neighboring cloud clusters in the storm.

There are conceivably three randomization schemes that could be employed for the single cloud experiment. These are 1) randomization between days, 2) randomization between storms, and 3) randomization between single clouds. Since the experimental unit is defined to be the unit to

*Throughout this section treatment is used in the general experimental sense i.e., one treatment is the use of a "placebo" or inactive material. Thus in a test of two seeding hypotheses (light and heavy), there are three treatments: small dose, large dose, and no dose (or placebo).

which the treatment (seeding) is applied (Steele and Torrie, 1960), the choice of randomization specifies the experimental unit. However, the *effect* of the treatment may be measured on the sampling unit, which can be the entire experimental unit or some fraction of the experimental unit (Steele and Torrie, 1960). Thus, if 'between-day' randomization is chosen, the experimental unit is the day and the sampling unit may be the single cloud. If 'between-storm' randomization is chosen, the experimental unit is the storm and the sampling unit is the single cloud. If 'between-cloud' randomization is chosen, the experimental unit and the sampling unit are the same -- the single cloud.

Assuming that adequate measurement systems for detecting the effect of seeding on single cloud complexes are developed, it is tentatively recommended that the treatment be randomized by storm but that the effect of the treatment be measured on a sub-set of the storm, namely the single cloud. Thus, it is recommended that the *experimental unit for the single cloud experiment be the storm and the sampling unit be the individual cloud.* In this scheme, if the "draw" was for seeding, all clouds in the storm would be seeded, to the extent that facilities permit, but effects of seeding would be sought particularly in those clouds that were actually seeded. If the draw was for no seeding, then none of the clouds would be seeded, but clouds which might have been candidates for seeding would be as closely monitored as if they had been.

The single cloud is rejected as the experimental unit because of l) the likelihood of interaction between clouds in multi-cloud convective systems, 2) the difficulties in cell recognition *prior* to treatment and hence the danger of sacrificing *a priori* statistical inference for *a posteriori* inference, and 3) the risk that the randomization may be invalidated because of possible contamination and because of the changing character of a single cloud (e.g., as would occur if the sample unit merged with another cloud). The choice of the cloud to be the *sampling* unit instead of the *experimental* unit permits the cell to be defined in a variety of ways without severely affecting the statistical inferences, and it also provides greater flexibility in testing physical hypotheses. Moreover, this scheme permits testing of hypotheses associated with interaction between adjacent clouds (e.g., enhanced mergers).

Although the single cloud should not be used as the experimental unit, the choice between the storm or the day as the experimental unit is not so clear cut. One advantage of the storm over the day is that it permits the more exact identification of the synoptic type for each experimental unit. Such a determination is not always possible if the day is used as the experimental unit, as, for example, in cases when fronts lie across, or pass through, the area, with convective clouds on either side. The dominating force in determining the character of the rainfall within a storm is the synoptic forcing, and it is quite conceivable that seeding effectiveness will vary substantially with synoptic conditions. Therefore, the ability to make this distinction removes an extraneous source of variation which, in turn, increases the precision of the experiment. A second advantage is that, if they are suitably separated in time and space, it is possible to have more than one experimental unit on a given day, thus increasing the sample size.

It Is recognized that there is a risk of contamination between storms, but the contamination problem can be handled either by allowing for a buffer period or buffer area, as given in the definition of the storm, in which no treatment takes place, or by skillful stratification during the analysis stage into categories based on the probability of contamination. The choice of the storm as the experimental unit also provides an opportunity to assess downwind effects if proper measurements such as suggested by Elliott, et al. (1974) are available to permit the tracking of the seeded and non-seeded storms into the downwind area. *It is noted, however, that the use of the storm as the experimental unit requires a method of storm recognition and delineation. Much useful information for defining storms can, and should, be gained from the HIPLEX operations in 1975-76, particularly from aircraft, radar and satellite observations. It is absolutely essential that the data be used to this purpose; if a method for real time delineation of the storm cannot be developed, the experimental unit will have to be based on the day instead of the storm.*

In the proposed scheme, the randomization would be conducted in the following manner: the storm (experimental unit) is delineated as it approaches the study area or as it Initiates in the study area. The storm would be Identified In real time by airborne scientists in radio communication with the radar. The entity must be clearly recognizable to both the airborne scientist by eyeball and the radar scientist, as an isolated echo or close group of echoes. If the storm Is designated to be a seeded storm, all clouds selected by the cloud seeding aircraft as suitable during the storm are to be seeded. (Suitability of a cloud is based on criteria developed from the hypotheses selected for testing.) The cloud physics aircraft monitors the physical characteristics of the seeded clouds until they dissipate or until they become so intense that they represent a hazard to the aircraft. If the storm is designated to be a non-seeded storm, clouds are selected in the same manner as if they were to be seeded, and the cloud physics aircraft monitors the storm system as before. (This is necessary in order to provide a valid control sample for the experimental design.) If additional seeding aircraft are available, they could be used to handle other incoming storms. This would provide another sample unit for evaluation based on the radar and dense raingage Information, even though cloud physics data would not be available.

A final point concerning randomization is related to its purpose in the weather modification experiment. Because of the rudimentary state of knowledge of the details of the processes involved in cloud and precipitation development, and the difficulty of predicting outcomes, it is necessary to rely on comparisons between treated and untreated cases. Randomization is required to ensure an unbiased estimate of experimental errors and/or treatment means and the differences between them. That is, randomization tends to destroy the correlation among errors.

To avoid bias in the comparison of the treatment (seeded and non-seeded means), it Is considered necessary to have a way of ensuring that the seeding cases will not be consistently handicapped by some extraneous sources of variation, known or unknown (Steele and Torrie, 1963). In order to achieve this admirable goal, the concepts of grouping, blocking, and balancing should be considered. Grouping is the placement of the experimental units into different groups so that they can be subject to seeding; this is accomplished by the randomization procedure itself. In blocking, the experimental units are allocated so that the units within a block are relatively homogeneous. In order to properly account for persistence, it may be wise to group experimental units into equal seeded and non-seeded samples (balancing). That is, blocking and balancing are an attempt to assure that the treatment is adequately "spread" over the differing meteorological regimes. Flueck and Mielke (1975) have suggested that variable blocks of units (in this case, storms) might be used which would have an equal number of seeded and non-seeded units (perhaps 2, 4, 6, or 8 experimental units).

The advantages of the proposed statistical design can best be illustrated by the various options of comparisons available. These include, among other possibilities; 1) comparisons between seeded and unseeded clouds, 2) comparisons between collections of seeded and unseeded clouds, and 3) comparisons between seeded and unseeded storms.

In regard to the first group of comparisons, it is recognized that the clouds (sampling units) are correlated with each other within the experimental unit. This correlation is allowed for in two ways. First, the clouds can be stratified according to the degree of correlation. The amount of correlation can be considered as a reflection of the physical nature of the storm system (i.e., isolated clouds versus imbedded clouds, air mass situation versus squall line, etc.). Thus, the stratification according to correlation can provide physical insight for the evaluation. Secondly, the second and third groups of comparisons do not involve correlations between clouds themselves; consequently, valid comparisons are available, while pertinent and useful cloud information is retained.

For the second group of comparisons, there can be any number of cloud collections. For example, Simpson and Woodley (1975) and Woodley and Sax (1976) used the "floating target", which is a collection of all seeded clouds (cells) and those that merge with them. Obviously, any collection of clouds used will be a floating target. Another possible collection of clouds would be the seeded clouds and all those that are within a specified distance of the seeded clouds. Comparisons between seeded and non-seeded collections stratified according to distance would provide an excellent method of testing for extra-area effects on the cloud scale. Furthermore, any of these collections can be compared to clouds not seeded during the storm for within-experimental-unit controls. However, caution should be exercised due to the possibility of inter-cloud contamination.

In the third group of comparisons, the characteristics of the storm are compared. In this regard, the total rainfall of the storm, the areal size of the storm, the duration of the storm, and the number of cells in a storm are examples of the parameters that might be compared in this group. In this way, the effect over the area can be assessed as well as the effect on individual single clouds and the experiment can be considered as a form of an "area" experiment. However, this is not the "true" area experiment which will be performed in Phase 3 which will treat complex cumuliform clouds as well as the simple, semi-isolated entities. *The physical* *mechanisms are different, and the "true" area experiment must not begin until an acceptable level of statistical and physical certainty is obtained in the Single Cloud experiment.*

In addition, other comparisons can be envisioned. For example, clouds which have a complete set of data measurements (i.e., cloud physics measurements, radar measurements, and ground rainfall measurements) could form a special class of comparisons. Another class would consist of those which have only radar and rainfall measurements, or those which have only rainfall measurements. Clearly, several classes of comparisons are available based on the quality and quantity of data. Consequently, the proposed statistical design provides an opportunity to make valid statistical comparisons, as well as the opportunity to use physical information and deduction in conjunction with the statistical design.

These choices of experimental units, sampling units, etc. presuppose that reasonable detection times can be achieved and that the different physical analyses and interests can be satisfied by such a design. As is shown in Section IV.C.2 and in Appendix B, both of these conditions can be satisfied by the skillful application of discriminant analysis to the design and evaluation problem, and by the development of the appropriate relationships for determination of the power of the test.

The statistical design group at ISWS will specify the requirements for the randomization to ensure appropriate grouping, blocking, and balancing as soon as the climatological and field data analyses provide enough information to do so. However, to guarantee design purity, the actual randomization (preparation of the treatment instruction) should be done by an independent statistical group, preferably one which has had prior experience in weather modification experiments.

For an in-depth discussion of the randomization scheme, the reader is referred to Appendix B.

2. Statistical Tests and Sampling Requirements

Since the emphasis in the single cloud experiment is on the removal of scientific uncertainty, the evaluation of the seeding effect will include tests of hypotheses regarding changes in cloud parameters as well as the rain at the ground. In addition, the samples will be grouped or stratified on the basis of "predictor" variables (Section IV.C.4) , i.e., parameters based on pre-treatment environmental, cloud and/or precipitation conditions which appear to have some influence on the development of cloud and precipitation. Under these conditions the application of a univariate statistical test to a single cloud or rain parameter has its limitations. Such a test has the distinct disadvantages of not utilizing the information contained in the other cloud parameters and, in some cases, overestimating or underestimating the importance of a particular parameter. It is far superior to provide a multivariate test, whereby the information in all of the cloud parameters can be utilized. The use of discriminant analysis can provide the appropriate multivariate test statistic in this case. This method has been successfully applied by Schickedanz (1974) to discriminate between characteristics of raincells exposed to differing urban and industrial influences. This technique is especially appropriate for the single cloud experiment since the storms are separated into randomized groups while the cloud parameters represent the basic components on which the physical effects are measured.

The discriminant analysis also provides an indication of which cloud characteristic is the most sensitive in distinguishing potential differences between seeded and non-seeded clouds. The most important advantage is that the discriminant function can include characteristics of 1) the radar echo (e.g., base height, top height, area of the echo base, etc.), 2) of microphysical or dynamical parameters (e.g., ice/water ratio) and 3) of the surface rainfall from the individual clouds. *This permits a tie-in between the physical events within the clouds and the rainfall that reaches the surface from these clouds. In a sense, the discriminant function provides a set of predictor variables for single clouds which can be used to remove extraneous sources of variation, thereby increasing the precision of the experiment.* All that is required is that a complete set of measurements of the variables be available for each sampling unit.

In order to estimate the sampling requirements for the test between cloud characteristics of seeded and non-seeded storms, a method to estimate the power of the test was needed. Since none was readily available, it was necessary to develop a method for estimating the power of a multivariate test based on the discriminant function. This development, as well as the extension to estimation of required sample size, is discussed in detail in Appendix B.

The previous discussion of the discriminant function involved an application to the sampling units. The discriminant function can also be applied to the characteristics obtained from the collections of clouds. Thus, parameters such as maximum rain, etc., as well as radar characteristics of the corresponding collection of echoes can be used. The discriminant function can also be applied to the storm parameters and the corresponding radar information. Thus, the correlation problem is most severe with the individual cloud comparisons, but, through stratification, the correlation problem is minimized and in fact can be used to yield additional physical information. The use of collections of clouds within the storm along with the total storm parameters in conjunction with the discriminant function eliminates the correlation problem completely, while incorporating useful and necessary information regarding individual clouds.

In order to develop the particulars of the statistical design and establish sampling requirements, a climatological data base of surface raincells and radar cells determined by the 5-cm radar system are needed. Unfortunately, such a data base is unavailable, although the analyses of the 1975-76 field data should -- must -- serve to fulfill at least part of this need. For the time being, METROMEX rain data from the period 1971-1973 have been used to obtain approximations needed for estimating some of the requirements of the statistical design as well as for determining the density, size, and placement of gages.

It is recognized that the surface raincell distribution can only serve as a first estimate and guide, since the raincell frequency is less than the frequency of seedable convective clouds. Furthermore, it is likely that the radar will show a greater frequency of "cells" than the raingage network. In fact the frequencies of radar echoes will probably be different from cloud frequencies also. Obviously, analyses similar to these being employed with the METROMEX raincells must be repeated for the radar and rain data obtained during the summers of 1975 and 1976 at the HIPLEX sites.

The estimated sampling requirements are given in detail in part 4 of Appendix B, following the description of the results of the METROMEX analyses which were done to arrive at these estimates.

These estimated requirements are based on multivariate tests of seven rainfall parameters derived from the METROMEX measurements for various hypothesized increases in each of the parameters, with and without stratification by synoptic type. These are tabulated for a 50-50 randomization (two treatments) in terms of years of experiment (assuming frequency of oppportunities equal to that in the METROMEX area). For a randomization of k treatments (non-seeded treatments included) where all seeded samples have a 50-50 randomization with non-seeded, the number of observations required are

$$N_k = N_2 k/2$$

The reader is referred to Tables B-9 through B-13 of Appendix B to get an idea of the sampling times required. *However these numbers should be used only as very roughly applicable to HIPLEX since they are based on the rain characteristics of an entirely different geographical region and precipitation regime.*

It is essential that the types of statistical analyses used in deriving these tables be repeated on the radar, cloud and surface rain "cells" observed in the High Plains during the summers of 1975 and 1976 in order to derive estimates appropriate for HIPLEX.

3. Variables to be Used in the Evaluation

In order to achieve the goal of reduction in scientific uncertainties, the evaluation must be based on the hypothesized effects in both the physical characteristics of the cloud and the rainfall. Since the predictions of the magnitude of these effects, by whatever method, are of low or uncertain accuracy, statistical comparison of seeded and unseeded samples as described above is an absolute necessity. This comparison should be based on the rates of change of significant cloud and rain parameters as well as the magnitudes of these parameters.

There are many parameters which may be used in trying to judge the effects of seeding on cloud and precipitation processes and on rainfall.

In Table 1 are listed the kinds of variables which should be measured before the treatment begins and then monitored during and following the treatment period. Monitoring should be continued until the cloud has clearly begun to dissipate, or until the cloud intensifies to the point

Table 1. Parameters Recommended for Evaluating Seeding Effects in Single Cloud Experiment (Critical parameters indicated by an *)

Variable

Group A - In situ upper cloud measurements, layer -8 to -15° C, evaluated for each significant cloud segment (i.e., each updraft, downdraft, and inactive region).

*1. Ice particle concentration (covering whole range of sizes) and rate of change, pre- to post-treatment.
2. Ice particle form and size.
*3. Total liquid-water content (peak and average).
*4. Partition of liquid water content into cloud, embryo and precipitation water.
5. Spectrum of the liquid condensate.
*6. Ice fraction of total condensate.
7. Updraft (downdraft) temperature.
*8. Net buoyancy in updraft.
*9. Updraft (downdraft) speed.
10. Estimate of the updraft (downdraft) dimension.
11. Duration of updraft.
12. Cloud structure in updraft (organized or groups of elements).
*13. Silver in bulk condensate.
14. Silver in individual ice particles.
15. Ice nuclei concentration.

Group B - In situ cloud base measurements.

*1. Updraft speed and estimated dimensions.
2. Duration of updraft.
3. Structure of updraft (organized or multiple thermals).
*4. Temperature and buoyancy of updraft.
*5. Droplet concentration.
6. Droplet spectrum.
*7. Height and temperature of cloud base.
8. Precipitation spectrum in rain shaft.
9. Areal extent of rain shaft.
10. Ice particles in rain shaft.
*11. Downdraft speed and estimated dimension.
12. Downdraft temperature.

Group C - Radar cloud measurements.

*1. Base and top heights and temperatures of the first echo, for non-echo clouds when selected as a sampling unit, and for new developments on all sampling units.
2. Rates of growth of tops of individual echo turrets.
*3. Rate of growth of top of main echo mass, as a function of time.

Table 1. cont.

*4. Maximum echo top for whole echo cloud.
5. Rate of fall of echo base.
*6. Time from first echo to surface echo.
7. Time series of maximum reflectivity of echo cloud and altitude at which it occurs.
*8. Volume enclosed by a specified reflectivity level.
*9. Maximum reflectivity for total duration of the echo cloud.
*10. Height and time (relative to first echo and/or first rain and/or time of treatment) of highest reflectivity.
11. Motion of echo cloud (speed and direction).
*12. Number of turrets or cells and position relative to treated cell(s).
*13. Duration of echo cloud.
14. Duration of developing stage of echo, where developing stage is defined by vertical or horizontal growth.
15. Area of echo base (at its greatest).
*16. Frequency of merging echo turrets or echo clouds.

Group D - Surface rainfall (see discussion of measurement, Section IV.C.5).

*1. Rainfall volume for each cloud.
*2. Area depth for cloud.
*3. Duration of rainfall from cloud.
4. Maximum areal extent of raincell (for some short period e.g., 5 or 10 min).
*5. Movement of raincell (speed, direction).
6. Average volume intensity (i.e., total rainfall volume divided by total time).
7. Maximum and minimum average point rainfall intensities (for some short period, e.g., 5 or 10 min).
8. Raindrop spectrum.
*9. Rainfall volume and area depth for storm.

Group E - Parameters available or derived from more than one source (e.g., radar, cloud photographs, satellite, etc.).

*1. Maximum cloud height.
2. Rate of rise of cloud top.
*3. Number of "turrets" or elements in single cloud complex and where they form relative to sample unit.
*4. Time from first echo to first rain.
*5. Time from start of treatment to first rain.
6. Precipitation efficiency.
7. Cloud size and spacing.
*8. Frequency of cloud mergers.

where it presents a safety hazard. This list should be refined during the pre-seeding period, both as to the best parameters and type of measurement (e.g., peak or average value, for cloud or draft area, etc.).

It is within available technology to measure all of the variables given, albeit with varying degrees of accuracy and coverage, and in all instances not as exactly as one would desire. This technology includes surface measurements, radar and in situ aircraft measurements. Of the three, radar provides nearly the areal and temporal coverage that is desirable but, since it is a remote sensor, contains major uncertainties as to quantitative measurement of most of the physical and rainfall parameters. A careful investigation should be made as to how the radar can be used in conjunction with the in situ measurements to "extend" them in time and space. This is treated in some detail in Section IV.C.5 for the determination of surface rainfall.

Aircraft measurements suffer most severely with respect to coverage because they are made along a thin ribbon in a medium which is highly variable in space and time. Thus samples have to be large in order to develop stable estimates of cloud properties. *A concerted effort should be made to investigate means by which radar measurements and model computations oan be used to alleviate this shortcoming,* if not in quantitative estimation, then at least in interpretation of results.

The evaluation should be based on at least two levels: the magnitude of the parameter at a certain time or stage of cloud development (e.g., maximum height of the cloud), or the difference between the values for pre- and post-treatment observations (e.g., difference in concentration of ice particles before and after treatment).

In some cases model predictions for natural (unseeded) conditions may be useful in providing a "base" value, and the difference between this base and the observed value used as the statistic for test. This approach has been used successfully by Simpson and Wiggert (1971) for maximum cloud top height. However the same statistic must also be determined for the unseeded sample unit. Models must be used with extreme care and reservation in the evaluation, both for this purpose and for extending the aircraft measurements, as suggested above. The one-dimensional steady state model is inadequate; the 1-D, time dependent model with complete microphysics and/or the 2-D model may approach realistic values; however they have not been adequately tested against observations. This should be done and then those predictions which appear to be the most realistic may be used to provide a base value for estimating change due to treatment or to provide an "estimator" for stratification purposes, as discussed in Section IV.C.4.

Most of the variables in Table 1 were selected to permit evaluation of the hypothesized changes itemized in Section IV.B.6 and/or to shed light on uncertainties listed in Section I.A.3. There are some, however, that are included either because there have been indications of modification in other seeding projects or because there is a likelihood that they might be modified. The variables have been divided into six groups depending on how the primary measurement is made. It is believed that many if not most of the variables can be determined with the systems already procured for HIPLEX, with perhaps exceptions of parameters In Group D (see Section IV.C.5) and Group A. Since intensification of the cloud and freezing of the water are the desired outcomes of seeding, the cloud physics aircraft in its 1975-1976 configuration may not be able to continue monitoring for the total period needed. Yet the cloud measurements around the -10°C level are most critical for satisfying the scientific objectives of the single cloud experiment.

Some of the parameters listed in Table 1 are more critical than others and some are simpler to determine than others. Crucial ones which can be measured with currently available instruments are indicated with an asterisk in Table 1. However many of the other parameters could be very instructive also. *Every effort should be made to measure those parameters which are specifically cited in the list of hypothesised effects* in Section IV.B.6, even if current technology permits only rather crude estimates.

This discussion has dealt only with monitoring of the characteristics of the experimental and sampling units for the evaluation. However it is equally important to monitor the state of the local environment during and following the experimental period. This is discussed further in the next section.

*4. Use of Covariates in the Evaluation

Independent variables which appear to have some relationship to cloud behavior and the production of rain have been used in one way or another in the evaluation of seeding projects for 20 years. The use of these "predictor" or estimator variables can greatly increase the sensitivity of the test by providing more homogeneous seeded and unseeded samples for statistical testing.

The predictors* can be of three types: a) environmental conditions on the synoptic, sub-synoptic and meso-scale, b) characteristics of the storm (the experimental unit) and c) characteristics of the cloud (the sample unit).

a. *Environmental Predictors*

Environmental predictors are parameters which reflect the control of larger-scale processes on local convection and precipitation processes. A master list of 200 candidate covariates found in a survey of the literature has been reduced to the 49 believed to have some applicability to the High Plains summer environment. The reduced set Includes 27 variables taken from soundings and 22 variables derived from objective surface field analyses. A pilot study based on these 49 parameters Is in progress using data for the month of June in western Kansas. The initial part of this pilot study has considered mean rainfall as the dependent

*Throughout this section the term predictor is used in its most general sense and includes covariates and stratification parameters as well as parameters that have a prediction capability.

variable and some 21 sounding variables and all of the surface variables as independent variables. A full description of the candidate predictors and of this initial phase of the pilot study is given in Appendix C. The results of the pilot study are incomplete and preliminary and it is premature to draw any conclusions. There were, however, some interesting results that are presented here very briefly.

After pre-screening 21 of the sounding and all of the surface variables separately by regression techniques, the "survivors" of both groups were used as a combined set of 14 independent variables (9 sounding, 5 surface). The bivariate zero-one, indicating rainless and rain days respectively, was regressed on the 14 variable set and a multiple correlation coefficient of .50, significant at the .01 level, was obtained. With area mean rainfall as the dependent variable, the multiple correlation coefficient was .38, also significant at the .01 level. Twenty-three percent of the variance in the mean rainfall (7-year sample) was explained by the combined set.

For the area mean rainfall, the most significant variables were the mean mixing ratio from the surface to the convective condensation level (WSFCCL), the 500-mb dew point, the 500-mb saturation deficit (negative correlation), and the terrain-induced vertical velocities based on the 0600 CST geostrophic wind and the 1500 CST observed wind. In general, the WSFCCL is a measure of the amount of moisture present in the subcloud layer. The terrain-induced vertical velocity may influence precipitation in two ways: 1) a wind with an easterly component will likely advect moisture into western Kansas and 2) the upslope flow may destabilize the troposphere and trigger convective outbreaks. The role of the 500 mb dew point and saturation deficit are somewhat harder to assess. It is possible that these variables may reflect the mountain-drift type precipitation system in which moisture is advected eastward over the plains at mid-levels. Or they may be indicative of deeper moist layers.

In the initial regressions, some commonly favored variables were screened out. The convergence, moisture convergence, cumulative lift (based on convergence) and pressure trough at the surface, all indicative of vertical motion and moisture flux, explained less than 4% of the rainfall variance. Furthermore, stability-related indices had low correlation with rainfall.

Again it is noted that these studies are yet incomplete. Other dependent variables are to be used in the study (e.g., rain characteristics based on hourly precipitation data, rainfall patterns) and many other independent variables are still to be tested.

In addition to those discussed in Appendix C, parameters derived from the one-dimensional numerical model, which are indicative of the day , will be tested as soon as they have been calculated for a suitable climatological period. One-dimensional model predictions are highly sensitive to updraft radius. Since horizontal cloud dimension is not available in the standard climatological base, (although there may be short periods of data in the WSR 57 logs), it will be necessary to be somewhat arbitrary in the choices of updraft size to be used in the calculation. Candidate parameters are calculated cloud top height and dynamic seedability.

Other potential predictors are antecedant rain parameters (average rainfall, coverage, etc.)» synoptic type, CCN and IN concentrations, etc.

b. *Storm Predictors*

Storm predictors reflect the influence of meso-scale processes on cloud and precipitation history and the interactions between the meso- and cloud-scale. There are a number of potentially good estimators of rainfall based on storm characteristics. These are

(1) Areal extent of storm,
(2) Cloud cover within storm,
(3) Duration of storm,
(4) General movement (speed, direction) of clouds within the storm,
(5) Movement of storm as a whole,
(6) General cloud characteristics at time storm declared an experimental unit (e.g., maximum cloud (echo) height, cloud-size spectrum),
(7) Thermodynamic stratification in storm area,
(8) Convergence in storm area .

All of these are determinable, some more exactly, some less, from satellite, photographic, radar, radiosonde and surface measurements. However some are potential response variables*, and there is a problem in specifying the time at which the variable is to be measured. During the actual seeding experiment, these parameters may be used in two roles: as a stratification parameter for single cloud data and as an estimator of the (unseeded) storm rainfall. In the first role, it is obvious that in most cases the measurement must be made before treatment begins. The one exception is item (4), which has been found to be an excellent covariate in the FACE analysis (Biondini, 1976). In this context item (3) is not a candidate parameter. In the second role, these variables may provide a "base" precipitation value from which to determine the observed "deviation", which is then used as the test statistic. In this second role it is more appropriate to the area experiment than the single cloud experiment.

Items (7) and (8) are meso-scale environmental parameters which have been discussed somewhat in 4.a. They are very important in cloud development and special observations or additional observing stations (surface, radiosonde or pibal) should be made if they are required to permit adequate estimation of these two variables.

The only existing climatological data base that would provide adequate storm information is the scope photography of the NWS WSR-57 network. Additional data may be available in the South and North Dakota Projects. Data suitable for at least a pilot study should be available from the HIPLEX field efforts in 1975 and 1976 and subsequent years.

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*Response variables are parameters that may change in response to the treatment, either as a direct or indirect consequence of the treatment.

c. *Cloud Predictors*

Empirical and theoretical studies have shown fairly convincingly that the precipitation produced by a cloud is a function of many cloud characteristics. Therefore observed cloud characteristics, prior to the start of the treatment on that cloud, could serve as good estimators of subsequent natural behavior and rain production. Candidate predictors range from general visual characteristics to measured parameters, such as

(1) Distance of treated cloud from other clouds in storm,

(2) Basic character of treated cloud, i.e., is it composed of a group of cumulus towers, (if so, how many), or a central cloud with satellites,

(3) Diameter of sample cloud,

(4) Cloud base temperature and height,

(5) Top height and temperature and/or depth of cloud,

(6) Total liquid water content in the region of -5 to -10°C,

(7) Existence of large drops and/or ice particles,

(8) Diameter and strength of updraft at cloud base and in activation region (-5 to -10°C),

(9) Net buoyancy in the activation region,

(10) Ice nuclei concentration.

Moreover, numerical models predict a number of cloud parameters which may prove useful as stratification variables. Dennis, et al., (1975) have used several predicted parameters in a single cloud evaluation of the Cloud Catcher project. This approach merits additional investigation. At the very minimum, one-dimensional time-dependent models should be used, preferably with complete microphysics, and the calculations should be based on observed initial conditions of cloud base and updraft diameter. Predicted parameters which should be considered are model predictions of

(11) Seedability of sample cloud,

(12) Maximum cloud top height,

(13) Updraft velocity profile and/or maximum speed,

(14) Maximum liquid water content.

These variables, observed and model predicted, should be screened in tests similar to those described in Appendix C. As in the storm predictors, a general data base for such a test does not exist. However, data from the HIPLEX field efforts in 1975-76 and subsequent years should be carefully studied to determine which of these parameters have true potential as estimators of single cloud rainfall.

5. Measurement of Rainfall for Evaluation

The specifications of a raingage network for the single cloud experiment are strongly dependent upon other aspects of the experiment. These include the statistical and physical design features and the method of evaluation of the seeding experiment. Operationally, a major consideration is the dependency which is to be placed upon weather radars for rainfall measurement.

In specifying raingage requirements, it is first assumed that a need exists to measure the volume of rainfall dispensed by a single convective entity as defined in Section IV.A. It is further assumed that entities to be studied are isolated sufficiently in time and space from each other to permit complete separation of the rainfall contributed by successive entities crossing the study area. These convective entities could then be either isolated, single-celled or multicellular rainshowers or thunderstorms. Previous studies in Ohio (Byers and Braham, 1949), Illinois (Huff, 1970; Schickedanz, 1973; Huff, 1975), and Florida (Woodley, et al., 1974) indicate that the single-cloud entities usually produce measurable precipitation over an area of 25-125 km^2, and occasionally over areas up to 250 km^2.

a. *Rainfall Measurement with Raingages Unsupported by Radar*

It is assumed that the basic rainfall measurement unit will be the total output (volume or mean rainfall) from each convective entity, although other rainfall parameters (such as areal extent, duration, and intensity) will also be used in evaluating seeding effects. From the standpoint of raingage sampling requirements, the use of very short-interval measurements of rainfall volume, such as 1-minute or 5-minute amounts, as a comparison standard is not considered practical for weather modification experiments. For example, in a study of one-minute rainfall amounts on a 50-gage, 100-mi^2 network in central Illinois, it was shown that the average sampling error with a gage density of 5 mi^2/gage (13 km^2/gage) ranged from 18% at rates of 2.5 mm/hr to 13% at 25 mm/hr (Huff, et al., 1969). In the same study, no significant improvement was found in the correlation between gages when 1-minute amounts were replaced by 5-minute amounts.

From consideration of Florida storms, Woodley et al. (1974) indicated a raingage network of 4 mi^2/gage (11 km^2/gage) would be required to measure rainfall adequately from individual clouds. Huff (1970) in a study of convective storms on dense raingage networks concluded that a network density of 10 mi^2/gage (25 km^2/gage) would be adequate for the detection and measurement of the areal extent of individual surface raincells 90 to 95% of the time. However, he also concluded that a network of 5 mi^2/gage (13 km^2/gage) is needed for measuring the rain output from individual raincells in the evaluation of cloud seeding experiments.

Experience with raincell analyses in the METROMEX network during 1971-1975 provides support for the conclusions by Huff and Woodley with respect to raingage sampling density. The areal extent of measurable rainfall from convective raincells averaged only 50 km^2 and the mean rainfall averaged only 0.75 mm. Elimination of raincells with areal means less than 0.75 mm and areas less than 25 km^2 still produced median values of only 2 mm and 70 km^2, respectively, for cell rainfall and areal extent. Sampling of such small phenomena requires much greater gage densities than required for total storm or daily rainfall.

It is concluded that the findings of Huff and Woodley provide the best estimates of gage density needed for the measurement of single cloud rainfall. Therefore, a gage density of 5 mi^2/gage (13 km^2/gage) is recommended where (and if) raingages are to be the sole means of surface rainfall evaluation. An investigation of raingage sampling requirements being made for the Bureau of Reclamation by Eddy, et al. (1975) may provide further knowledge on this subject in the near future.

All raingages in the target and control areas for the single cloud experiment should be of the recording type to provide space-time distributions of rainfall for the individual convective entities. Tipping-bucket or weighing bucket gages should be used for the measurements with the latter preferred unless telemetering is to be employed. The gages should have the capability of measuring 5-minute amounts for accurate delineation of the time distribution characteristics of single-cloud rainfall. The ERTS gage, in its current state, does not have satisfactory time resolution. With weighing-bucket gages, use of gears that provide 6-hour revolutions of the recorder chart is recommended. Weekly revolution of the charts should be avoided, but 24-hour chart revolutions can be used with some sacrifice of detail in the time distribution pattern.

Within the limits of the existing road system, the raingages in the research network should be located in a uniform grid system. A strong effort should be made to locate the raingages so that they do not depart more than one mile from uniform spacing. The network should be in the shape of a circle or square for sampling all types of storm movements.

The use of raingage shields is not recommended for convective rainfall measurements. The cost-benefit ratio is too small in view of the small gain in accuracy from shielding. For example, a study at the Illinois State Water Survey (unpublished) indicated that differences in storm rainfall catch between Alter-shielded and unshielded gages were usually of the order of 1 to 2%, and rarely reached 5%. Studies at the Water Survey have shown that the shape of gage housing can produce differences as great or greater than differences observed between shielded and unshielded gages in convective rainstorms. Consequently, if two or more types of raingages are used in the research network, a comparative study of their catch efficiency is recommended so that adjustments can be made to allow for catch differences that may be significant.

The optimum size and sampling density of the research network cannot be specified from raingaging considerations alone. This is dependent upon such factors as 1) the size of the target area, 2) precipitation climate and length of the experimental period (sample size), 3) the evaluation requirements (level of statistical significance), 4) the rainfall comparison standard (raincell, rainstorm, etc.), and 5) the extent to which radar is used for rainfall measurements. Item 5) is discussed below; the other factors are treated elsewhere in this report.

b. *Rainfall Measurement by Radar*

The requirement that the evaluation of the single cloud experiment include surface rainfall presents a serious problem. As indicated above, measurement by raingages alone would require a very high density network. Because of the size of the area that will probably be needed to get a significant sample in a reasonable length of time, the use of raingages alone may not be feasible. It is a general feeling that neither raingages nor radar used alone can yield the desired accuracy. Some combined system using raingages (and/or raindrop spectrometers) and digital radar is desirable to obtain adequate coverage and accuracy.

Two main problems have to be addressed with regard to radar: 1) an assessment of the effect of attenuation of 5-cm radar waves on the radar's ability to measure rainfall, and 2) an assessment of numerical techniques by which a radar-raingage mix can provide the necessary rainfall measurements for HIPLEX.

The attenuation problem. Several readily available texts adequately set out the theory of attenuation, practical definitions of terminology, and present the state of understanding of the topic (e.g., Battan, 1973). A literature review (Appendix E) indicates that no true measurements of 5-cm attenuation have been made. No evidence has been advanced, however, to argue against the validity of the theoretical predictions of attenuation from Mie theory at this wavelength, as long as the attenuating precipitation is liquid water. When hail is present in the precipitation signal, evaluation becomes extremely complex.

There has been, in the past, a general consensus that quantitative measurement of rainfall requires 10-cm radar. Hamilton and Marshall (1960, estimating attenuation by rainfall at 3, 5, and 10 cm from raingage statistics, calculated that 5-cm estimates of season-total heavy-shower rain would be 26% below that calculated from 10-cm measurements. On the other hand, in precipitation regimes where rainfall rates are generally low, the attenuation problem is not so severe and 5-cm radar may be a reasonable choice (Harrold, 1965). There has been evidence (Geotis, 1975; Sirmans, personal communication) that the attenuation at 5-cm wavelength can be as much as 15 db through heavy rain storms (see Appendix E for further discussion).

There have been attempts to develop techniques for correcting radar returns for attenuation, with only moderate success. These however are applicable only in the absence of ice; in the presence of hail the corrections can themselves be in great error.

The problem of attenuation at 5-cm is a serious one for it can introduce so much error into the measurement of rainfall as to obliterate the changes introduced by seeding unless they are very large. It is essential that the 5-cm attenuation be determined before finalizing the rainfall measurement studies. The field studies planned for the summer of 1976 in Montana (discussed below) address this problem, among others.

Radar estimation of rainfall. There are many references in the technical literature pertaining to studies on the estimation of rainfall by radar (see summary in Appendix E). Almost all concentrate on the search for Z-R regression formulae. These formulae, of which there are many (Stout and Mueller, 1968) are only the roughest estimators of precipitation, a factor of two average error in point estimates being typically the best one can expect. This is inevitable since the estimation is very sensitive to the drop spectrum and this varies, not only from day-to-day or storm-to-storm, but also within each storm. There have been many attempts at predicting the best Z-R regression for a given meteorological situation but the improvement in accuracy by these methods has not been spectacular.

c. *Rainfall Measurement by a Mixed Radar-Raingage System*

In spite of the low accuracy of Z-R equations in estimating mean rainfall by radar, when compared to the raingage spacing generally available (e.g., 1 gage/200-400 miles) they can provide an improvement in the measurement of storm mean rainfall. Gages are the best estimators of point rainfall, errors due to wind, splash, etc. being estimated at about 10% or less. But, as indicated above for convective rain which is highly variable (short durations, small overall dimensions and sharp gradients), an extremely large number of gages is required to estimate total rainfall to any desired accuracy.

In recent years several investigations have been made to evaluate the utility of radar (usually 10-cm) in the quantative measurement of rainfall. Results are in general agreement that a significant improvement can be made in the measurement of areal-mean rainfall where dense raingage networks are not available,by using 10-cm radar in combination with available raingage data. There have been two basic developments: a) the cluster technique employed by Woodley, et al. (1974), and b) the Brandes (1975) error-field technique.

The cluster technique utilizes a small number of sets of closely clustered raingages to determine a Z-R relationship to be applied to the radar field elsewhere. The basic assumption is that as a storm moves from the clusters to the catchment of interest there is no significant change in its Z-R characteristics. It relies on the presumed existence of an all-day or all-storm Z-R relationship.

Using clusters of raingages adjacent to a densely-gaged meso-network of 220 mi^2 for radar calibration, Woodley concluded that their gage-adjusted WSR-57 (10 cm) approximates a gage density of 25 km^2/gage for measuring storm rainfall over large areas. However, they also found that the radar could not meet their requirement that shower rainfall from individual clouds be measured within a factor of two in 33% of the cases. They further concluded that over a small sampling area (500-800 km^2) that a raingage network with a gage density of 25 km^2/gage will consistently out perform the gage-adjusted radar, and a density of-10-11 km^2/gage (4 ml^2/gage) will provide their desired measurement accuracy. A distinct problem with this approach arises in its application to weather modification experimentation. If a storm passes over the clusters and is then seeded, it may reasonably be argued (Cataneo, 1971) that the seeding will alter or destroy the relationship between Z and R previously established. Some observational grounds for this were reported by Jones, et al. (1968).

It is likely that the radar performance can be improved further by use of the method proposed by Brandes (1975), in which raingage observations are used to derive a field of radar calibration factors for adjusting the radar-observed rainfall distribution over the sampling area. The Brandes error field technique consists in determining, at each gage of a network, the ratio, E, between the gage-estimated rainfall, and the rainfall estimated with radar by means of a fixed Z-R regression formula. In practice the radar data are averaged over some area centered on the gage. The values of E at all the gages are then analyzed by an objective technique to produce a correction factor for each point of the radar data field. This amounts to adjusting the radar field to fit all of the gage points. It implicitly rejects the search for a Z-R regression entirely. In fact it assumes that none exists in the sense of previous studies, but that a relationship exists at each point for the time period of the measurement. Justification of the objective analysis-of the error field rests on the assumption that the spatial variations of the factors which contribute to the error are all adequately sampled by the available gage network.

Wilson (1975, 1976) has implemented the Brandes gage-radar ratio approach over the Lake Ontario watershed for IFYGL. He concludes that the average gage-adjusted radar precipitation estimates will be in error by only 10 to 20%, provided the sampling area is ≥ 100 km^2, rainfall integration > 3 hours radar range of 50-100 km, calibration gage densities > 1/3000 km^2, rainfall amounts ≥ 1 mm/hr, and data collection frequency > 12 times per hour. Concerning the question of how much improvement is obtained with the radar-raingage combination over raingages alone, Wilson points out that this is very dependent upon 1) the length of measurement period, 2) the size of sampling area, and 3) rainfall variability.

The above generalizations by Wilson are useful, but not specifically applicable to the HIPLEX single cloud experiment in which we are concerned with small convective entities of short duration and small areal extent, rather than storm rainfall summed over several hours.

Still another limiting factor in optimizing the measurement of rainfall with radar is the natural time variability of radar reflectivity in convective storms. The effect of this factor on gage-adjusted radar estimates, such as those utilizing the Brandes method, has not been established. In view of the foregoing uncertainties, it is concluded that we do not have adequate data and information available at this time to assess properly the accuracy achievable in the measurement of single cloud rainfall through use of various combinations of radar and raingage observations.

Assessment of the Brandes technique applied to 5-cm radar must await results of the exploratory phase of HIPLEX during summer 1976. Unless seeding-induced increases in single cloud rainfall are extremely large (of the order of 50%-l00%), the gage-adjusted radar estimates must provide an accuracy equivalent to that obtainable with a raingage network of 5 mi^2/gage (13 km^2/gage). Woodley and associates were unable to achieve this level of measurement accuracy with cluster calibration in Florida. It remains to be seen whether the spatial correction method of Brandes will do this without utilizing a calibration network closely approaching the density of 5 mi^2/gage specified earlier for a raingage network unsupported by radar measurements. When an adequate data sample has been collected, the optimum design of rain measurement system (mix of raingages and radars) can be defined. A sample of at least 100 raincells from 10 or more storms is needed for the radar-raingage design evaluation.

d. *Research to Evaluate 5-cm Radar/Raingage Mix*

As has been clearly shown above, there are many problems associated with adequate rainfall measurement. Some critical ones must be resolved before a measurement system can be designed for HIPLEX. The State Water Survey will be carrying out research during FY-77 to evaluate the capability of the 5-cm radar-raingage mix. This research will be based on the raingage and radar data collected in Montana during the summer of 1976. In addition ISWS will be operating 10 disdrometers in the Montana raingage network. A primary objective of the ISWS research will be the evaluation of the Brandes technique and its performance in the presence of attenuation (see discussion in Appendix E).

D. Operational Aspects

1. Base Operations

The fulfillment of the intermediate goals of the HIPLEX on the single cloud seeding experiment requires 1) coordination and communications between the operating components, and 2) real-time weather information providing long and short term forecasts, where long term is on the order of a day and short term is on the order of hours.

The establishment of a *Forecast Center* at the experimental sites is recommended to accomodate the specialized, site-specific forecasting needs for field operations. The reaction time between a locally changing weather condition, that is cumulus development, and implementation or alteration of an operation precludes the utility of forecasts prepared at either a central HIPLEX facility or National Weather Service regional forecast centers.

The *Forecast Center* personnel would be expected to develop site-specific forecasting techniques to maximize the skill of selecting operational days and minimize loss of effort due to inaccurate predictions. In addition, a valuable function of the *Forecast Center* personnel will be to catalog, for real-time and post-experiment predictor variable analysis, a list of meteorological variables obtained from local observations.

The Ingredients for a successful daily operation include briefings on weather and equipment status prior to field activities, and debriefings on data quality at the conclusion of an operation. A status report on the availability of personnel should also be communicated at the briefing sessions.

In this section, requirements to fulfill the projects needs to carry out the day-to-day tasks will be addressed. Each task will be described and followed by recommendations. These descriptions and recommendations universally apply to each of the sites involved in the HIPLEX.

a. *Personnel Responsibilities*

The *Site Director* is responsible for the overall completion of the site project. The *Director* will relegate responsibility to others as required, but will retain ultimate control of the overall operations. The person in this capacity should reside in the community nearest the site operations center to provide communications with the user-citizen of the area.

The *Director* will monitor and, if possible, maintain control over special research studies and operational seeding programs which may be either on-going within or in proximity to the project area so as to minimize interference with the prime objectives of the HIPLEX seeding experiments. Operational seeding outside the HIPLEX program is in progress or planned for areas adjacent to all three sites. DAWRM should attempt to work through State agencies to minimize the nearby operations. Nevertheless, there is a good possibility that operational seeding will be going on during the seeding experiment. Arrangements should be made for daily communication with the operators of these programs and for obtaining complete daily logs of their seeding operations, including times, amounts and locations of the release of the material.

The *Director* will be responsible for assimilating advice from a group of project supervisors and a local citizens committee, and rendering decisions for the conduct of daily operations. A description of the areas of responsibility for each of the supervisors is contained in the following.

The *Forecast Supervisor* must be a qualified person with considerable knowledge of, and preferably experience with, the local climate and weather. This person is one of the key personnel with responsibility to prepare and issue morning and evening forecasts for operations and provide intermediate analyses as required during rapidly changing weather situations. Numerical modeling predictions and objective analysis tools should be utilized in support of the normally prepared forecasts. The operation of the *Forecast Center* will require support personnel for at least two shifts during the single cloud experiment to provide current National Weather Service data as soon as available for forecast revision. It will be the responsibility of the *Forecast Supervisor* to declare the day meteorologically suitable for operations. This information will be transmitted to the *Director* as part of the decision-making process for implementing seeding missions.

The decision with regard to the daily operations will be reached in two phases. The first phase will be the preparation of a preliminary forecast each evening which will be given to the *Director* for use at the debriefing session. As a result of this preliminary forecast, the personnel and equipment involved in the project may be placed on alert for possible operations on the succeeding day. The second phase will be accomplished during the early morning with the preparation of the final forecast for the briefing on the day of potential operations. At this time a declaration is made with regard to the day's activities insofar as the weather is expected to be conducive to a seeding operation (see section IV.D.3). Henceforth, continuous monitoring of the weather situation is required in order to either abort or initiate an operation due to a rapid change in the local weather patterns. There is a strong need to continuously monitor the weather to identify potentially hazardous weather conditions, i.e., those that will lead to very heavy rains, hailstorms, and strong windstorms, even when severe storm watches or local flooding have not been forecasted.

It is the responsibility of the forecast team to advise the *Director* of severe weather outlooks including flood warnings. When a severe weather watch is issued by the National Weather Service for the experimental area, all seeding operations will cease. It will be the responsibility of the *Director* to continue or abort seeding operations in all other circumstances. At the discretion of the *Director*, research measurements may continue in order to provide a maximum amount of data for characterization of convective systems in the climatic region.

The *Forecast Supervisor* will be assisted by personnel familiar with the preparation of weather charts and graphs to provide current analyses of the synoptic situation. It will be necessary to operate the weather station between 0600 and 2000 hours local daylight time to ensure maximum information availability to the on-duty forecaster. These hours should be extended if the seeding operation continues beyond 2000. Radiosonde observations should be taken routinely for forecasting purposes. Special soundings should be taken as deemed necessary by the *Forecast Supervisor*, particularly under uncertain or critical weather conditions. In addition, soundings should be made periodically (every 2 or 3 hours) during actual operations for use in analysis and evaluation.

A *Radar Supervisor* shall have the responsibility for supervision of the radar operations, including aircraft control. It will be his responsibility to advise the *Director* of the status of readiness of the radar systems and personnel. It will also be his responsibility to identify potentially good cloud areas and to direct the aircraft to them. The decision that a cloud area (storm) is to be designated an experimental unit will be made by the meteorologist aboard the high-altitude airplane in consultation with the *Radar Supervisor.* Therefore it is necessary that the *Radar Supervisor* be a radar meteorologist with experience in cloud physics and/or weather modification programs.

Continuous communications between the operational radar site and the forecasting headquarters must be maintained so that the *Radar Supervisor* can be provided with continuous updating of the weather situation. A communications link must be established between the radar facility and the forecast facility, if they are physically separated. It is, of course, highly desirable to have all facilities co-located to minimize errors in communications and maximize the interactions between project personnel.

Experienced aircraft control personnel are required to assist with navigation of the aircraft in proximity to convective storm systems. It is preferred that a radar devoted to this task be made available with the capability of providing continuous position data of the aircraft in 3-dimensional space. There should be a permanent record made of aircraft positions at very frequent intervals (every few minutes) either by scope photography or automatic recording. A second radar is required for use as a seeding evaluation instrument and also as a cloud physics tool. This radar will provide quantitative reflectivity information for interpretation by the *Radar Supervisor* and the aircraft controller. If not physically present, the *Director* must be in communication with the *Radar Supervisor* and the aircraft controller for the purpose of making emergency decisions with regard to the operations. A radar engineer must be on duty and available within approximately 10 minutes during actual operations of the seeding effort so that failures of the systems can be corrected without delay.

The *Field Observing Supervisor* will be assigned the responsibility of assuring maximum capability of the surface equipment and personnel. The *Field Observing Supervisor* will advise the *Director* of the status of the surface network as input for the overall decision regarding operations.

The *Director* will also be advised daily by the *Aircraft Operations Supervisor* as tb the status and availability of the project aircraft. This is another key area of responsibility and will require a person familiar with the aircraft equipment, knowledgeable as to their mission capability, and conversant with the pilots and crews.

Finally, the *Director* will be advised through the *Citizens Committee* (see Sec. VII.A.1) regarding the cumulative soil moisture conditions. Such an interaction with the local population is deemed highly desirable to thwart operations which are opposed by the immediate area user (farmer, rancher, etc.).

b. *Facilities*

A base of operations must be provided with sufficient space for the *Director's* office and support personnel, forecasting operations, radar operations, equipment maintenance, and special project operations. The normal equipment for a weather station with forecasting operations will be required. This equipment should include: 1) weather facsimile, 2) pilot balloon capability, 3) A and C teletype circuits, and 4) standard weather observation instruments. The radiosonde team should also operate at the base facility.

At least two seeding aircraft are desirable in order to permit treatment of more clouds during a given operational period and/or to permit treatment of more than one storm on a day. In addition, an airplane capable of making cloud base measurements and a second one capable of making upper cloud measurements, as itemized in Section IV.C.3 and 4, are required. The pilot or an observer on all aircraft should have had meteorological training and/or experience in weather flying. There must be a communications link between all aircraft as well as between the aircraft and the radar controller. All aircraft should be equipped with transponders to the base radar for tracking purposes.

Adequate hangar space is required for these aircraft. It is recommended that the seeding materials and the seeding aircraft be separated or isolated from the scientific airplanes. It is necessary that precautions be taken against contamination of the scientific airplanes which will be collecting condensate for silver analysis.

Standardized calibration procedures should be scheduled on a frequent and regular schedule for all equipment. It is *absolutely necessary* that very careful calibrations and checks be made of the radar system daily by the radar engineer to minimize the experimental error in measuring Z. In addition,a target calibration should be made at least once a season. Careful pre- and post-program flight and bench calibrations should be made for all aircraft instruments and frequent field and flight checks should be made during the field effort. Readings of surface instruments, particularly raingages, should be checked at each servicing. Procedures should be established for scanning all kinds of data for instrument malfunction as soon after the data are taken as is possible.

2. Seeding Operations

There are four levels of decision required in the seeding operation: l) declaration of an operational day, 2) declaration of a storm area, 3) selection of clouds for treatment, and 4) specification of treatment.

The individual responsible for declaration of an operational day is the *Site Director.* The declaration of a storm area will be made jointly by the meteorologist aboard the high altitude airplane and by the *Radar Supervisor.*

The selection of clouds for treatment will be made by the personnel aboard the upper level aircraft, according to established criteria (see Section IV.D.3), and the locations transmitted to the seeding aircraft. The person making the selection may ask for information from the other aircraft or the *Radar Supervisor.* However experience in cloud flying and/or weather modification projects would be highly desirable. The technique for application of the treatment must be a blind one, if at all possible, so that the kind of treatment is -- and remains -- unknown to the person selecting the clouds. It is preferable that it also remain unknown to the individuals doing the basic data processing and analysis.

The treatment for the storm will be specified by instructions that must remain unknown to the key people at the field site and most particularly to those identifying the storm and selecting the clouds. There are a number of ways in which this can be done. To some extent the final method, and whether such secrecy is feasible at all, will depend on the seeding technique which is used. The statistical group making up the treatment instructions should have input into the development of mechanisms by which these instructions are to be passed on to the field people once a day has been declared operational. Examples of how this can be done for pyrotechnic or solution seeding agents while ensuring the purity of the experiment follow.

The use of dummy flares or a dummy solution is highly desirable. If a dummy is used, it should be laboratory tested for production of ice nuclei and cloud condensation nuclei to make sure that it is not a nucleating agent. The Agl and dummy units can then be packed in identical crates which are identified by number. A master list identifying the agent for each number may be retained by the manufacturer of the units, by the statistical group making up the treatment instruction and/or by a single individual in the Bureau of Reclamation, until the final analysis stages. During the final analysis, the identification of live versus dummy agents will be made known before final data stratification by seeded and unseeded storms.

Instructions for the numbered treatment to be used on the declared experimental unit are determined from sealed envelopes or a master instruction list prepared by the statistical group. If the experiment includes more than one technique (e.g., cloud base and cloud top seeding), the specific technique will also have to be specified in these instructions.

3. Identification of Operational Days and Suitable Clouds.

a. *General Atmospheric Conditions*

To a large extent, convective cloud and precipitation development is controlled by the larger (sub-synoptic and synoptic) scale conditions of the atmosphere. It is important, both from operational and evaluation considerations to properly identify the opportunities which are favorable for cloud seeding. With regard to day-to-day operations and efficient use of resources, this is a forecast problem. Objective criteria to identify the meteorological conditions leading to various kinds of cloud conditions can be very useful in forecasting and, moreover, may be effective in attaining the blocking and grouping needed for the statistical design. Of particular interest for the single cloud experiment are those conditions favorable for the development of convective entities of the types specified as single cloud in Section IV.A. and which have a good potential for producing rain.

It is desirable, if at all possible, to identify the synoptic, sub-synoptic and thermodynamic parameters which, in combination, lead to one of the following conditions: 1) suppressed conditions, 2) scattered shower clouds and/or clusters of well-spaced shower clouds, 3) line of well-spaced showers or small thunderstorms, 4) squall lines and/or large multi-celled storms, and 5) severe storms. The second and third conditions are most suitable for the single cloud experiment. The covariate studies described in Appendix C may help in identifying the more sensitive parameters for predicting these conditions.

Pending results from these analyses, the information accumulated from High Plains projects has been used in schematically outlining the factors which may be important. Most of these projects have drawn upon predictors that address at least one of three physical states important to convective rain-producing systems. These are the stability, the availability of moisture, and the dynamic triggering mechanism. All of the studies applicable to the HIPLEX sites (Montana, Kansas, Texas) show that convective precipitation is highly correlated with the depth of the moist layer and the presence of a dynamic trigger. The spatial and temporal transience of the dynamic triggering mechanism is suspected to partly explain the poor correlation between convective precipitation and stability calculated from early morning soundings.

In Figures 13 a-c are shown flow charts which may be used as guides for objective forecasts for each of the HIPLEX sites. In all of the flow charts, days rejected first are those when the available moisture is insufficient to support deep convection. Then a search is, made to find a dynamic trigger. If there is none, there remains the possibility that air mass showers may develop if the expected daily maximum temperature, T , exceeds the convective temperature, T . The anticipated areal coverage of showers is then determined as a function of moisture. There are no references to stability aside from its inclusion in the SWEAT Index, which is included to identify possible severe storm producing conditions.

The Montana objective forecast flow chart (Fig. 13a) was constructed from information presented by Dennis, *et al*.(1967) and Hartzell (1975). More emphasis is placed upon the dynamic trigger (mid-tropospheric trough, front of any kind, convergence zone, squall line, etc.) as these systems account for most of the summertime precipitation over the High Plains (Bark, 1975; lleichter, 1974; Dennis *et al*., 1974). Further, the poor correlation between precipitation and stability can be explained if the principal precipitation producing mechanisms are transient in space and time. For Kansas the section that treats overrunning in Montana has been replaced by a section that treats post cold front showers (Fig. 13b) on the basis of recent Kansas studies (Bark, 1975). In Texas, (Fig. 13c) the low level flow can rapidly advect moisture in from the Gulf of Mexico (Girdzus, 1976).

These charts have not been tested or used operationally and should be considered only as general guidance for study. Numerical criteria such as are given for precipitable water and the SWEAT Index are highly approximate. It is recommended that the forecasters at the HIPLEX sites further develop these, or similar methods, based on their experience in both 1975 and 1976, for order of importance, actual numerical criteria where appropriate, increased specification (e.g., exact nature of the -triggering action), and additional factors of importance, such as the predictions of the 1-D steady state, model.

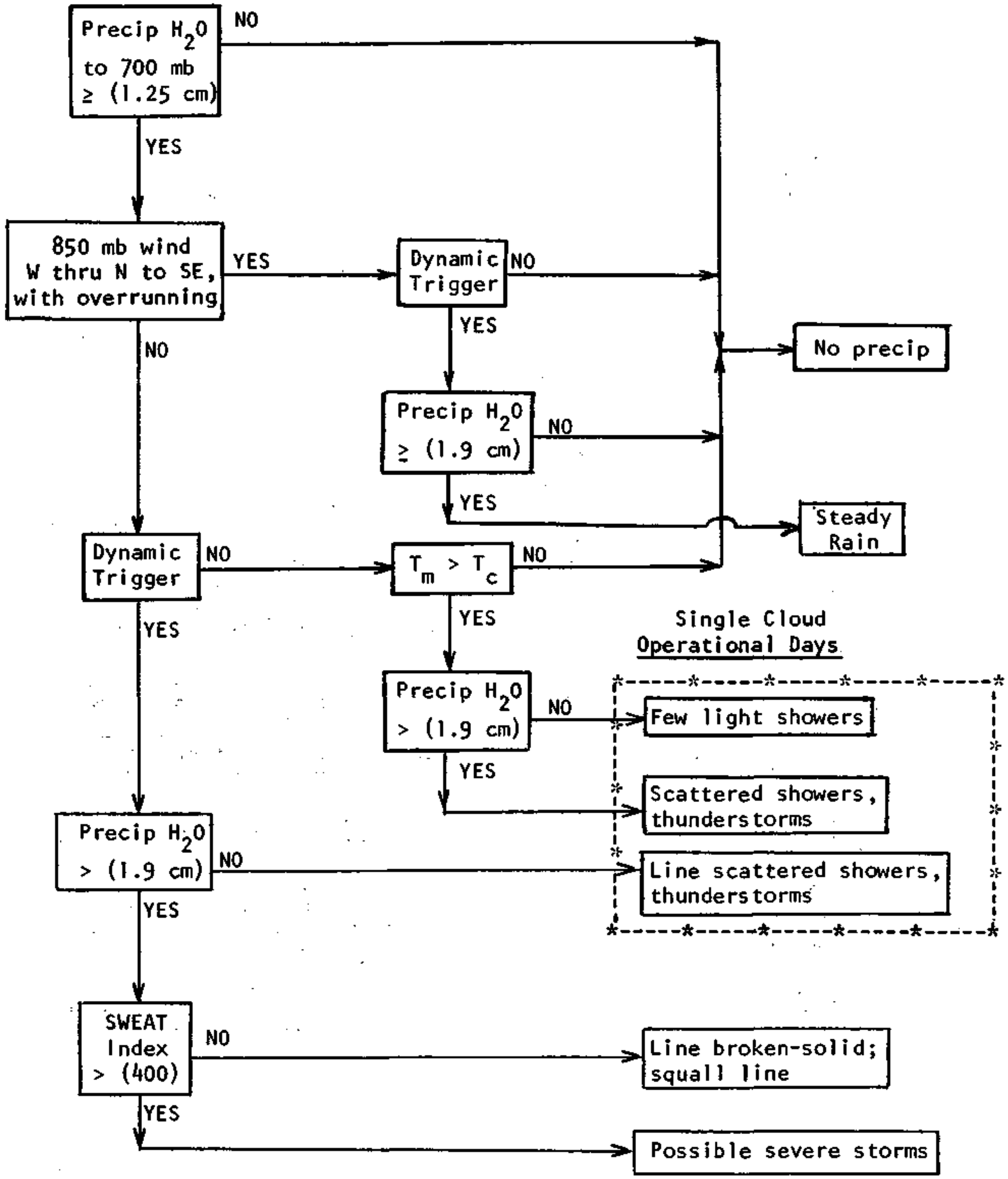

Figure 13a. Flow Chart for Objective Forecast for Miles City area in Montana.

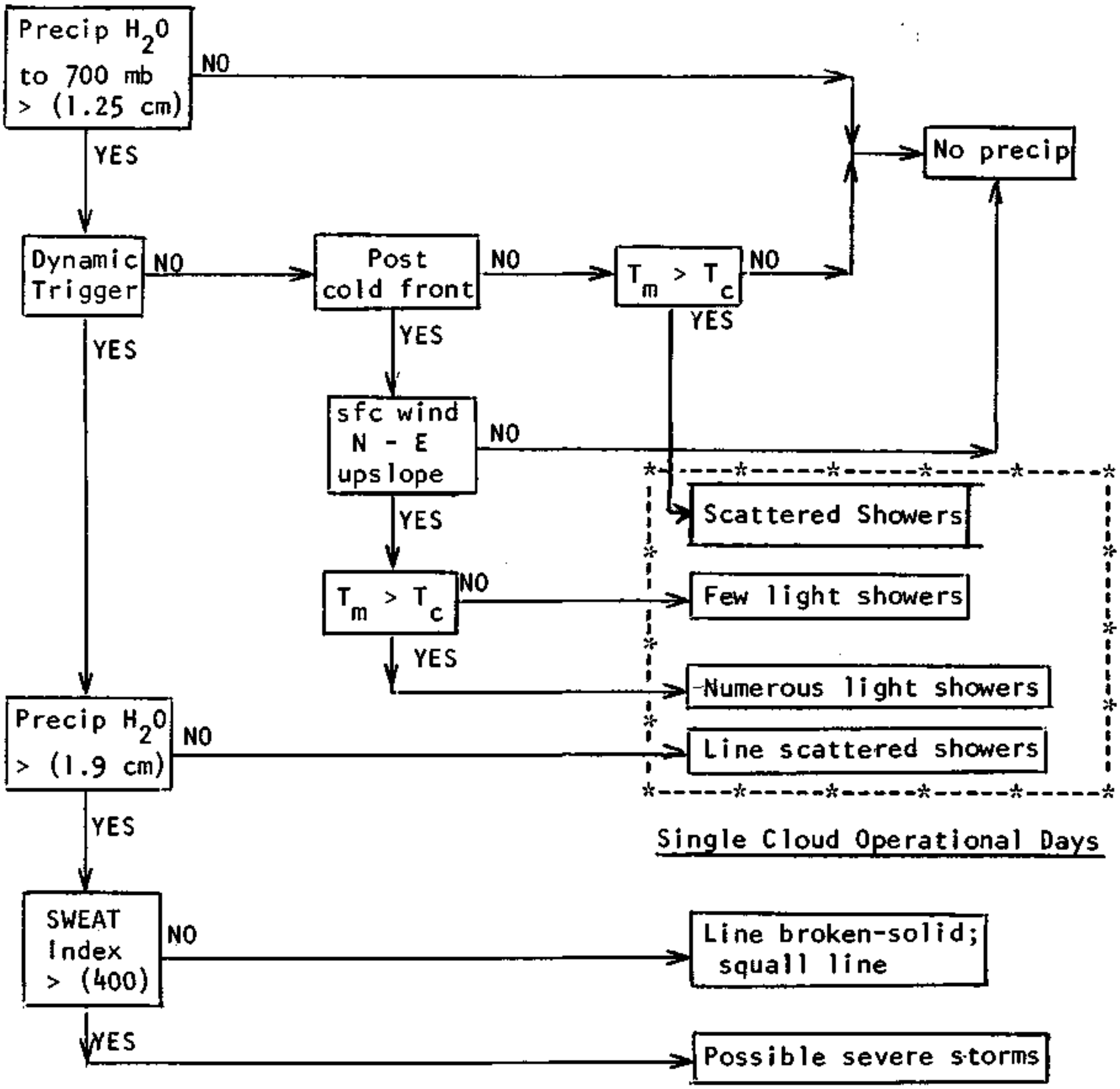

Figure 13b. Flow Chart for Objective Forecast for Colby, Kansas site.

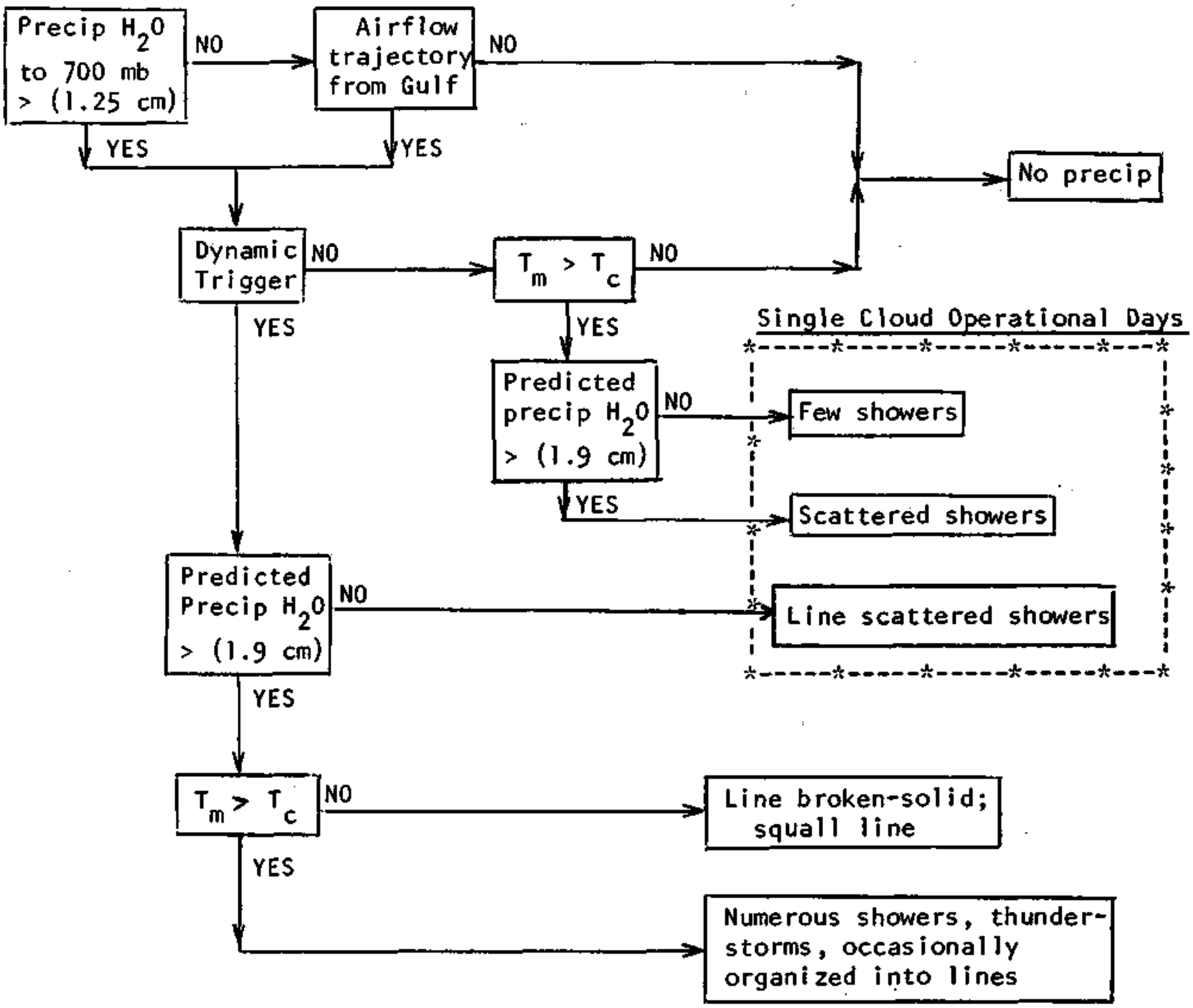

Figure 13c. Flow Chart for Objective Forecast for Big Spring, Texas site.

b. *Suitable Clouds*

Ideal general cloud conditions for the single cloud experiment are widely scattered showers or small thunderstorms, or a group of well-spaced shower clouds or a line of well-spaced shower clouds or thunderstorms. Given these conditions, it is necessary to select particular members of the cloud population for treatment. A suitable cloud candidate must fit the definition given in Section IV.A. for the semi-isolated single cloud, namely an identifiable convective entity which may have several convective elements but which is definitely separate from other clouds. In addition it must show strong signs of being in an actively developing stage. This is usually indicated by obviously growing turrets, with hard sharp outlines.

The cloud should be "blocky" in appearance, i.e., its horizontal dimension should be at least two or three kilometers although the updraft need not extend throughout the cloud mass. The seedability predictions of the one-dimensional cloud model may be used as a guide for setting criteria of cloud diameter on a given day.

If cloud seeding is to be at the cloud base, the seeding aircraft should be able to locate a significant updraft of at least 1 or 2 mps extending for several hundred meters. Moreover, some of the cloud turrets should be penetrating the freezing level at the time the treatment starts. If the seeding is to be from above, the seeded turrets should be penetrating the -5 or -10°C level. There should also be evidence of an updraft.

There have been a number of reports from different parts of the United States which indicate that most echoes which develop in convective clouds of the type specified for the single cloud study have very short lifetimes and do not grow significantly after first detection. Preliminary analysis of the data collected in the Big Spring area in 1975 (Carbone, private communication) indicates that this may also be true in the High Plains. The cloud candidate need not be giving a. precipitation echo, but if it does, the echo should be growing or should extend through only a fraction of the convective complex, or the visual, appearance of the cloud must give signs that the cloud is not yet near its peak intensity.

In cases where the cloud selected is a small cumulonimbus with adjacent clouds, the larger and most active of the latter, which is <u>upwind</u> of the glaciated anvil, should be chosen as the sampling unit rather than the main cloud. Clouds penetrating the -20°C level are not suitable for treatment since precipitation is likely to have been initiated by the ice process.

V. AREA EXPERIMENT

In the area experiment the cloud systems of interest cover the whole range of convective rains, from small semi-isolated showers to convective cells embedded in extensive and multi-layered cloud decks. Whereas the main target of the single cloud experiment is scientific understanding, that of the area experiment is establishing confidence in producing significant increases in rainfall at the surface. Thus this phase is, ultimately, the critical one for meeting the overall goal of HIPLEX.

A major goal of the single cloud experiment is to provide the physical basis on which to develop the area experiment. Also it will identify the most promising techniques for modifying convective clouds. It is, in a sense, part of the exploratory studies that form the basis of the design of an area experiment. Thus it is premature to discuss the design of this third phase except in a general way.

It is essential to develop background information on <u>all</u> of the warm season cloud and precipitation systems for the area experiment. Some studies are already in progress, namely those based on standard climatological data. Phase 2, in both the pre-seeding field efforts and POCE, offers the opportunity to develop the more critical climatologies related to general structure of the cloud system and to the cloud physical parameters.

It is recommended that during the field efforts of Phase 2, the radar be operated and data recorded during <u>all</u> cloud periods, even those that are not suitable for the single cloud experiment. The only exceptions are, of course, periods of highly suppressed convection. These radar data should be analyzed for parameters (e.g., areal extent, cell intensity and dimension, etc.) significant for precipitation formation in order to provide critical information for formulation of the hypotheses. Moreover this information is needed for developing the precipitation measurement system — a very important consideration since the evaluation will rest on the surface rain.

In applying the physical understanding gained in the semi-isolated single cloud to other convective clouds having a modification potential, the question of how universally applicable the results of Phase 2 are, will have to be faced. Thus it is essential that cloud physics measurements be obtained in all types of clouds that are or could be rain producers. Thus a systematic data collection and analysis program should be instituted for clouds not meeting the "single cloud" criteria. This is especially necessary for the northern plains where widespread cloud systems may occur with significant frequency.

The use of the storm as the experimental unit offers a good lead-in to the area experiment. The analysis of the POCE should include storm area analysis. Due to the selective seeding, only a fraction of the clouds will have been seeded and therefore the seeding effect will be diluted. Nevertheless it should be possible to develop "scenarios" with which to sharpen the statistical design.

It is anticipated that extensive seeding will be employed in the area experiment. Thus the problem of extra-area effects (effects of seeding in areas outside of the immediate target area) can be addressed. An integral part of the area experiment will be careful studies to ascertain if the target seeding had any modifying effect on the cloud and precipitation beyond the local area and if so, the mechanism(s) by which these were effected. The extra-area and downwind effects and methods of studying them are discussed in Section VI.

VI. ATMOSPHERIC IMPACTS

A. General

The atmosphere is an open system, governed by a complex array of Interdependent processes. There has never been, nor Is there likely to be in the near future, any means for controlling cloud systems. Precipitation modification hypotheses are universally based on triggering a particular microphysical process and then letting nature take its course. As has been previously noted in this report, the complexity of the cloud processes makes it very difficult, at this stage of understanding, to predict exactly nature's course, even for a single cloud. The consequences of seeding on the environment around the cloud, on adjacent clouds, on subsequent cloud development both within the target region and around it are equally — if not more — difficult to predict.

The speculation that seeding could have effects far downwind of the target area first surfaced in the early 1950's when Langmuir publically stated that the modification experiments carried out under Project Cirrus in New Mexico may have played a role in producing the very heavy rains in the Kansas River Basin in the spring of 1951, which resulted in disastrous floods along the lower Kansas and Missouri Rivers. More recently, the question of downwind effects has been the subject of a number of statistical studies associated with various seeding experiments (Brier, et al.,1974; Elliot, et al.,1974; Neyman, et al .,1973; Schickedanz and Huff, 1970). The extent of downwind effects is still controversial, but must be faced in HIPLEX.

In addition to the far downwind impacts, there may also be more local effects within the target area. One obvious possibility is that if,through dynamic enhancement of a cloud,the flow of moisture is increased, there may be a suppressive effect on other cloud development in the immediate area. Under these circumstances the areal-mean rainfall may not be changed — and in fact it may be decreased.

B. Physical Mechanisms

There are a number of mechanisms which may operate to produce secondary and higher order effects both locally and outside the primary target area of the precipitation modification. These are the same as those acting naturally during active convection. Some candidate mechanisms are:

(a) *Stabilization by return settling.* In response and opposition to the strong upward flow in convective clouds there is a downward flow of air which negates an accumulation of mass in the upper troposphere. It is not known over what area this flow takes place but it is clear that it causes some degree of warming and stabilization of the middle troposphere. The smaller the area over which the downflow takes place, the greater its velocity and the greater the depth of the warming. Some of the downflow may take place within the storm and there is evidence that some takes place in the immediate vicinity of the developing towers of a single cloud. At any rate, stabilization of the non-cloud environment would have a suppressive effect on cloud development, and hence on precipitation in the stabilized region. Any influence which enhanced this (e.g., stimulating the growth rate of a single cloud) serves to enhance the suppressive effects elsewhere.

(b) *Gravity waves.* Strong, unsteady vertical flows in the atmosphere, of which cumulus convection is one example, are likely to generate gravity waves if the atmospheric stratification is such as to support such waves. Gravity waves move away from their point of origin at speeds determined by the atmospheric stratification. Attention has focused in recent years on the possibility of gravity waves triggering convection and severe weather. If seeding results in increased and/or accelerated cloud growth, it could result in the generation of these waves and, consequently, convection and precipitation in some places well away from the seeding area. This, in turn, might suppress it in others by the process discussed in (a) above.

(c) . *Lifting of potentially unstable air by gravity flows of cold air.* Some thunderstorms develop downdrafts which exhibit a great degree of organization. The downflow of cold air, presumably created by evaporation of rain into dry air at middle levels (about 6 km AGL), is highly localized and, at the surface, spreads out as a cold front. The coherent movement of such thunderstorm-generated "squall fronts" to great distances (several hundred kilometers) from their source is well documented both by satellite observations and by more traditional means. These cold air flows can trigger convection in areas remote from their origin. Again, where strong convection occurs at one place, there may be a suppression of convection elsewhere. Any influence altering the storms producing the cold flows will alter the character of the cold outflows and hence the spatial and temporal character of the results they produce.

(d) *Development of bigger systems by cloud merging.* Independent and separate clouds are known to "merge" or grow together frequently, particularly when at least one is a well-developed shower cloud or cumulonimbus. The merged system is longer-lived and larger than the individuals and is a better rain producer. The mechanism by which the merger takes place is a matter of speculation, but hydrodynamic forces must play an important role.

Seeding to enhance cloud growth is hypothesized to result in such mergers (a key hypothesis in the Florida Area Cumulus Experiment, Woodley and Sax, 1976). The merged system could result in increased precipitation laterally (relative to cloud motion) and, due to its longer lifetime, in the immediate downwind region due to cloud motion.

(e) *Effects of anvil outflows.* Generally, the wind structure of the environment in which thunderstorms and showers take place is such that air rising through the updraft of a storm is swept away from the top of the storm in a direction determined by the upper winds. Even though the storms themselves tend to move in the same direction, the upper tropospheric winds are generally much faster than the middle level winds with which the storms move. These high altitude cirrus plumes can extend hundreds of miles downwind from the generating cloud and fifty miles or more in width. The shadow cast by such shields can markedly reduce the solar heating of low-level air in the area it covers, limiting the development of instability and hence of other shower and rain production. Satellite observations yield examples of the suppression of convection by such upper cloud layers.

At the same time there are other effects due to anvils. It has been proposed that ice crystals fall from anvils (and other cirrus clouds) into the upper portions of cumulus clouds, seeding them and causing them to produce rain or hail. Also, at the boundaries of the shadows cast by the plume, the differential heating pattern can create gradients of temperature (hence air density) which resemble fronts and which can become sites of new convection.

(f) *Effects due to wetting of the ground by rainfall.* Thunderstorms and showers produce large amounts of rainfall over relatively small areas. The wetting of the ground due to this radically alters the fluxes which compose the energy balance at the ground. The reflectivity of the wet surface will be different to some degree; the conductivity of the soil will be affected to some depth; incoming solar energy will be used to evaporate the water, reducing the energy available for heating the surface. The effect of this altered balance on the air density, and hence of instability and buoyancy, will depend on the exact balance which occurs. At any rate, the wetted area becomes a greater source of water vapor and will tend to remain slightly cooler than surrounding, unwetted areas. This must influence convection and precipitation, both remotely and locally, to some as yet unestablished degree. Considerable research effort is currently being expended to attempt to detect effects on the weather due to crop irrigation which should be similar to (but probably stronger than) those due to natural rainfall.

(g) *Effects of uncontrolled transport of the artificial cloud seeding substance.* Once cloud seeding material is abandoned to the cloud system, its fate is somewhat uncertain. Some of it is active locally in bringing about the desired change in the cloud system; some is scavenged by the precipitation processes and washed out of the atmosphere. Some will be swept downwind along with other cloud material, or remain in the air with the evaporating cloud residue. Some may remain on the ground and vegetation and later be returned to the atmosphere, or react with solar radiation and other substances in the atmosphere to produce other products. The influence of these uncontrolled quantities on subsequent weather, locally and remotely, is a topic of intense interest to the weather modification community.

(h) *Surface winds and other effects.* The strong, damaging winds produced by severe thunderstorms and hailstorms are a manifestation of the downdraft phenomena. The strong, organized downdraft of such storms is caused by the evaporation of rain into very dry air encountered at some distance (2 to 5 km) above the ground. This evaporation chills the air and lowers its density to the point that it becomes negatively buoyant. The chilled air acquires considerable kinetic energy during its descent which is diverted into the horizontal near the ground. Winds approaching 50 mps due to this cause are not unheard of. Any process which alters the production of precipitation in the storm will alter the rate of production of cold air in the downdraft, and hence, to some unknown degree, the strength of winds and gustiness at the ground.

C. Monitoring of Extra-Area Effects

Most of the factors cited in B, above, are more relevant to the area experiment than to the single cloud experiment. However, these potential effects can be studied for natural, unmodified cloud systems, and monitoring of this type should be initiated during the exploratory and POCE phases of the single cloud experiment. Monitoring of the local effects on surrounding clouds and convection within the storm must be an integral part of the single cloud experiment.

Randomization by storm in the single cloud experiment simplifies monitoring of the local effect of seeding within the storm and on surface effects of the storm. The following should be monitored during the single cloud experiments:

(a) Total convection within storm (size, maximum height, duration of clouds within the storm and the number of clouds within storm), using satellite and radar observations primarily.

(b) Storm rainfall (number of events, durations, average intensities), using surface raingage data.

(c) Storm intensity (hailfall, wind gusts, and lightning) from surface instrumentation.

Randomization by storm also permits study of some downwind effects such as

(a) Frequency and size of cirrus shields from satellite measurements.

(b) Changes in storm character as it moves downwind of the experimental area, by satellite and radar.

(c) Development of new storms around the seeded storm, by satellite and radar.

During the area experiment itself, the effort to establish downwind effects must be an essential part of the experiment. <u>In addition</u> to the downwind effects listed above, the following factors should be monitored in the downwind area.

(d) Silver in precipitation.

(e) Storm hailfall, lightning, and strong winds.

(f) Most importantly, surface rainfall.

Measurement of potential extra-area effects will be required many miles downwind of the target area. For the evaluation of the effect of the area seeding on downwind surface rainfall, it is anticipated that raingages will need to be employed. The National Weather Service networks, regular and cooperative, should be used but will probably have to be supplemented by additional gages. Non-recording gages or the much cheaper wedge gage (about

$3 each) evaluated by Huff (1955) can be useful in the study of extra-area effects where dense recording-gage networks are too expensive. However, recording gages should be interspersed to provide some information on the time distribution of the extra-area rainfall, and an approximation of the rainfall intensity. It is anticipated that total storm or daily rainfall would be used in the study of extra-area effects, particularly during the area experiments. Under these conditions, an overall gage density of 25 km^2/gage is recommended with the interspersed recording gages having a density of 125 km^2/gage. This combination will measure storm mean or daily rainfall with an acceptable accuracy and the recorders will detect most of these events. The foregoing estimates are based upon studies of sampling error and storm detection in Illinois (Huff, 1970), and should be modified as data are accumulated from networks in Montana and elsewhere. A detailed description of the measurement and analysis procedures for the area effect (including atmospheric impacts) is being developed.

VII. USER INTERACTIONS AND SOCIAL, ECONOMIC, AND ENVIRONMENTAL STUDIES

All four phases of HIPLEX (Background Studies, Single Cloud Experiment, Area Experiment, and Technology Transfer) should involve an integrated series of activities 1) to assess the various impacts of the weather modified by HIPLEX, 2) to inform all interested parties of the activities and consequences, and 3) to conduct the experiments within a proper social, legal, and environmental framework. Failure to perform adequately the recommended Social, Economic, and Environmental Studies (SEES) will lead to a range of serious and detrimental outcomes for the meteorological experiments, regardless of their scientific success (Changnon, 1975). Proper integration of local and regional individuals and groups in the experiments, including certain operational decisions, will sustain public and scientific acceptance and will ultimately lead to much more effective technology transfers. Inadequate attention to SEES-type efforts in most past weather modification experiments either has led to a variety of problems affecting the project activities or has limited utilization of the results in other areas. Good meteorological research in weather modification experiments can be cancelled by improper assessments of impacts and inadequate public relations. It is extremely important that the planning for the atmospheric research, and in particular field operations and data collection, be done in conjunction with the planning for the data collection in the social, economic and environmental phases of the project.

An estimate of the cost of a SEES effort to cover the essential tasks would be at least $350,000 annually and hopefully $500,000 for all recommended tasks at the three sites. The total activities and effort recommended fall within two general areas: informational-interaction activities and impact assessment studies. They are interactive, and the informational activities are also to be interrelated with the actual meteorological experiment and its results.

An overview of these two activities and how they should interrelate in time (Phases 1 through 4) is offered in the flow diagram labeled "Impact Studies and Informational Activities" (Fig. 14). The interactions of the meteorological experimentation with the users and public are shown on the left, whereas the interactions of the SEES with the users is shown to the right. The recommended activities and research under these two broad areas, user interaction and SEES, are described in the following sections.

A. User Interactions

An essential part of HIPLEX concerns the interface between 1) the users plus the public, and 2) the meteorological efforts (the background field studies and then the experiments) and the results of the SEES. A user is a person who is directly affected by the outcome of the project or one who perceives that he (she) is affected. The public in the project area are not necessarily users, particularly those who reside in larger urban centers where altered weather has no real or perceivable impact. Before the field efforts and experiments are launched, a carefully presented program to inform the

IMPACT STUDIES AND INFORMATION STUDIES

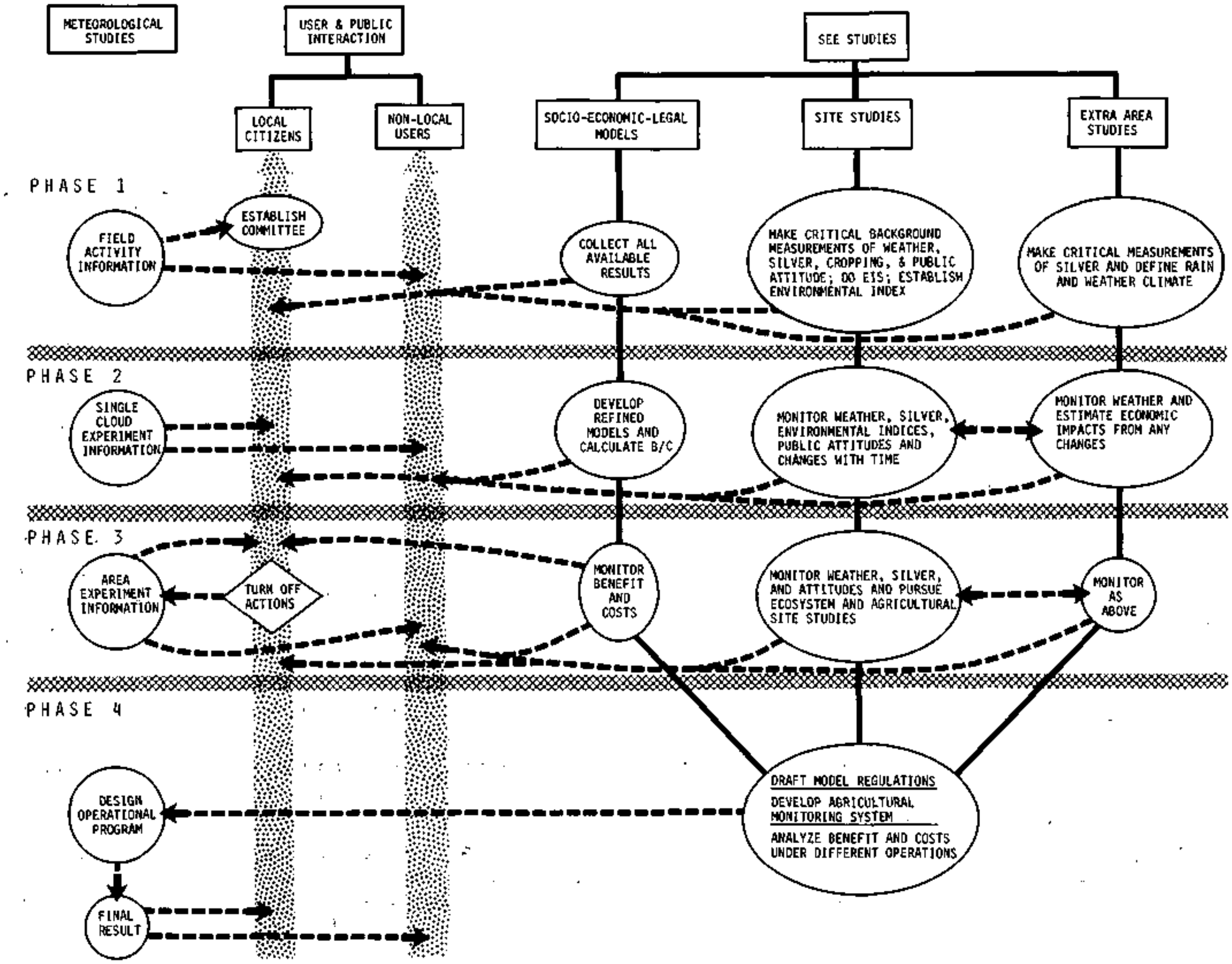

Figure 14. Flow diagram providing an overview of the impact and information activities and their interaction.

TABLE 2a. SOCIAL, ECONIMIC, AND ENVIRONMENTAL STUDIES

Phase 1 — Exploratory Studies

ENVIRONMENTAL	ADMINISTRATIVE AND LEGAL	SOCIAL	ECONOMIC
Establish background levels of silver in principal components of area ecosystem*	Prepare and file EIS*	Assess with a formal sociological project the reaction of area residents to: a) Cloud seeding *per se* b) Seeding only isolated clouds Phase 2*	Describe pre-experiment cropping patterns in detail*
Summarize existing results from previous studies of grassland responses to additional rainfall and seek environmental index species for use in monitoring rainfall change*	Establish liaison with related modification programs (research & operational)*	Survey wide range of 'pre-experiment' attitudes**	Summarize existing results from crop-response models*
Establish background levels of silver in principal components of "downwind" ecosystem**	Develop specific stop/go guidlines for severe storm situations and for excessively wet and drought conditions*		Characterize area's representative farm unit and/or ranch as input to later economic modelling**

* Essential activities
** Desirable activities

TABLE 2b. SOCIAL, ECONOMIC, AND ENVIRONMENTAL STUDIES

Phase 2 — Single Cloud Experiment

ENVIRONMENTAL	ADMINISTRATIVE AND LEGAL	SOCIAL	ECONOMIC
Monitor silver accumulation in principal components of ecosystem*	Secure appropriate licenses & permits*	Monitor any organized responses to Phase 2 activities*	Estimate "break-even" level of effectiveness for isolated-cloud modification and consider economic impacts of altered weather conditions other than rain*
Monitor all related weather conditions (temperature, humidity, severe weather including strong winds and lightning, cloudiness) in study of impacts and any changes on seed/no-seed basis* (This also relates to economic studies.)	Agree upon & establish mechanism (at local & regional levels) for dealing with potential allegations of liability*	Check for post-experiment changes in knowledge and attitudes*	Determine the (area-specific) marginal uses and value of incremental water*
Check for silver in precipitation in downwind area, and monitor silver accumulation in downwind area*	Employ stop/go guidelines in severe storm situations and excessively wet and drought conditions*		Estimate economic impacts of any detectable extra area changes in precipitation or cloud cover *
Carry out silver uptake studies**			Carry out water-response studies of full range of area's crops**
Carry out ecosystem response studies (modelling)**			Estimate energy savings and effects on municipalities implied by additional water supplies**
Studies of microbial response to silver complex concentrations in soil & water			Estimate price effects of additional crop production**

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* Essential activities
** Desirable activities

TABLE 2c. SOCIAL, ECONOMIC, AND ENVIRONMENTAL STUDIES

Phase 3 — Area Rain Experiment

ENVIRONMENTAL	ADMINISTRATIVE AND LEGAL	SOCIAL	ECONOMIC
Monitor silver accumulation in principal components of ecosystem*	File up-dated version of EIS*	Monitor any organized responses to Phase 3 activities	Estimate "break-even" level of effectiveness for area modification
Carry out ecosystem response studies with index species*	Employ a stop/go approach to experimentation based on extremely wet and drought conditions*	Check for "post" experiment changes in knowledge and attitudes**	Identify key elements of efficient operational precipitation augmentation program (e.g. size, facilities, etc.) and costs*
Check for silver in precipitation in extra area and monitor silver accumulation in extra area**	Study legal implications of interstate programs of operational precipitation modification**		Estimate secondary economic (multiplier) effects*
Carry out silver uptake studies**			Demarcate sub-areas of High Plains where direct benefit/cost ratio >1 under expected levels of effectivness*
Study effects of precipitation changes on plant pests and pathogens**			Perform computer simulations of shifts in cropping patterns**
			Estimate utility-value of increased stability of income stream**
			Carry out area-specific hydrologic (e.g. run-off/erosion) studies**
			Refine existing temperature-precipitation interactive response models**
			Model impacts on livestock sector**

* Essential activities
** Desirable activities

TABLE 2d. SOCIAL, ECONOMIC, AND ENVIRONMENTAL STUDIES

Phase 4 — Technology Transfer

ENVIRONMENTAL	ADMINISTRATIVE AND LEGAL	SOCIAL	ECONOMIC
Develop cost-effective system for continuous monitoring of silver levels in soil & water for use by operational programs*	Draft & circulate a "model" set of regulations for the control & monitoring of operational programs of precipitation augmentation*	Develop public response models for use in attitude sampling and developing policy actions for operational projects*	Analyze distribution of costs & benefits under a variety of financial schemes for operational programs*

* Essential activities

** Desirable activities

public about the project must be initiated. Past sociological studies of weather modification generally point to a favorable public attitude towards weather modification prior to experimentation. These samplings of public attitude have revealed that, for a science like weather modification, which is complex and difficult to understand, the majority of the public tends to depend on key local (township, city, and county) decision makers for opinion development. These decision makers vary and may include farmers, bankers, clergy, mayors, elected county officials, extension agents, and conservation district directors. Thus, one major interactive public relations effort concerns the local (the people in and around the experimental area) users and interest groups (agribusiness representatives, county agents, city commissioners, farm organizations, etc.)

1. Local

In Phase 1 of the project at any one site, the key people must be identified *in and around* the 200-mi^2 area, and then systematically informed about all aspects of the experiment. A project (site) information officer, most likely the Site Director, should be identified to give talks and to answer questions. Presentations to these small groups have to be honest and internally consistent. Short concise project information documents should be developed for wide distribution. A "citizen's committee" composed of these key local citizens should be developed at each site of HIPLEX. It will serve as a focal point for a continuing interface throughout the project.

The second part of this local public interactive effort during Phase 1 of HIPLEX (and again in Phases 2, 3, and 4) involves working with these local decision makers to develop a series of public presentations to key groups (service clubs, 4-H groups, farmer unions, etc.). The single cloud seeding experiment (Phase 2 POCE) should not be launched until these aforementioned activities are well initiated and a favorable and understanding local response is obtained. Among other things, this will aid in the local arrangements for instrument siting, a major effort, and in protection of instruments from vandals.

During the experimental phases (2 and 3), the public in and downwind of each area should be routinely and continuously informed through the news media and citizen's committees about the progress of the project. The extra-area or downwind studies (Fig. 14) of altered weather, silver deposition (if any) and economic impacts specifically should be reported routinely in the area beyond the target area. The project activities and status regarding experimental days could be announced over local radio stations, and summaries of annual results should be delivered to the public and to the local and state officials. All possible existing means for distributing information, such as the university extension services, should be used to distribute project information about specific items of lay interest both on a regular and special basis.

A valuable aid to the public information needs and to the project results should involve, at the start of Phase 2 (Single Cloud Experiment), the establishment of a network of cooperative weather observers. Weekly reporting cards allowing for the entry of daily rainfall, hail, and other comments should be furnished, along with wedge raingages (at no cost) to all interested citizens. Tours of the project facilities should be arranged for local citizenry on fixed dates.

A major consideration for Phase 2 and Phase 3 concerns public involvement in temporary halts to the experiment due to existing weather conditions. The contingencies, for altering the experiment need to be presented to the local citizenry before the experiment begins. There are three weather conditions which could demand a change in the experiment. One relates to both Phase 2 and Phase 3 and involves meteorological decisions to halt experimentation, on the time frame of a day or less, when extremely severe weather is likely in the study area. It is clear such provisions must exist. These must be defined by climatological and meteorological studies of severe weather conditions that will provide criteria for forecasting conditions of sufficiently severe nature that experimentation should be halted (such as predicted conditions leading to tornadoes ≥ F4 level, surface gusts ≥ 60 mph, rainstorms ≥ 25-year point frequencies, or hail > 1 inch diameter). However, the severe weather levels chosen to indicate a stoppage of the experiment should not be so restrictive as to limit the experimental units to too few days. The principal action here is to clearly inform the local user and public of these shutoff conditions.

The second temporary halt or turnoff action for the experimentation directly relates to the public during Phase 2 and 3. Here, provisions should be made in the statistical design and in the operation of the project for temporary halting of experimentation under extremely wet conditions. These can be defined in various ways, such as saturated soil moisture or rainfall in excess of 4 inches in any given 7-day period over 80% of the study area. These criteria of delineating excessive local wetness need to be defined objectively during Phases 1 and 2 in concert with local agricultural experts. They also should be directly involved, during the Area Rain Experiment, in providing the needed information as to moisture levels (if soil moisture is to be used) and the areal extent of the wet conditions. The decisions to stop and go rest on these data. The loss of experimental data and costs due to any such stoppages will be outweighed by the benefits accrued in presenting a responsible attitude and maintaining a defensible legal posture. Furthermore, such cutoff procedures will exist in all well-performed operational modification programs. In the experimental region, an individual (possibly also a member of the Citizen's Committee) should be identified as being responsible for transmitting information on wet conditions to the Site Director.

The third circumstance affecting the conduct of field experimentation, both in Phase 2 and Phase 3, concerns the incidence of drought in the research area. Every effort should be made to continue the experiment during dry periods and drought conditions. However, it is recognized that the areas of experimentation are occasionally subject to severe droughts that can destroy or drastically reduce crop yields, pasture and forage, and local water supplies. In these severe conditions, there may likely be strong local and regional interest in temporarily halting the experiment so as to utilize weather modification on a full time basis. Procedures should be adopted that allow for such a halt in the experiment.

It is recommended that limits be set, in concert with local experts, as to those levels of dryness (such as in soil moisture, rainfall deficit, and USDA predicted departures of crop yields below expectations) and areal extent of dryness (within the experimental area) that will be objective criteria used to stop the experiment in favor of an operational, full time modification effort. It should be the responsibility of the local advisors (such as the county farm agents) identified to advise the Project Director of an imminent dry condition and a foreseeable need to temporarily stop the experiment. Similarly, the end-of-drought criteria must be agreed upon to allow re-initiation of the experiment. The conditions whereby the local advisory groups can declare a stop or start of the experiment in favor of a non-experimental operational seeding project aimed at addressing severe drought must be defined and agreed upon before the single cloud and area experiments begin.

If a temporary operational project is adopted, we also recommend that the experimental facility and staff not be employed to conduct the operation. Such involvement will eventually destroy local support and belief in the need for the experiment and will hurt the scientific credibility of the experiment. The experimental staff and facilities should be used to evaluate the results of the operational project. If circumstances dictate use of the experimental elements (staff and facilities) to perform the operational program, a non-committal stance towards the project and its results is recommended.

Phase 4 (Technology Transfer) should involve, at the local level, dissemination of final results in a "lay" version. A recommended product of the final HIPLEX effort is the design of a model operational program for the region.

2. Non-Local

The other major interactive effort concerns individuals and interest groups comprising basically non-local users of the project results. These non-local users include affected businesses, scientists, agricultural interests, and various governmental entities.

One of these groups is the crop-hail and property insurance interests (companies and their associations). Successful weather modification will have a major impact on this industry, and they will wish to be closely informed of the progress and performance of the experiment. Further, their involvement should be sought in the form of furnishing detailed daily loss data for the project area. Their endorsement of the experiment is also sought so that local insurance representatives will understand the project and its potential value to them.

Another group of non-local users includes various agriculturalists at state universities, agricultural associations such as the Farm Bureau, and major agribusinesses involved in the regional (High Plains) agriculture. Rain alterations, if successful, would affect them in various ways. The strong and influential reputation of the agriculture experiment station in each state and the agricultural associations also means that it is wise to inform these groups about the project so as to secure their understanding and to utilize their communication channels. Key officials in these agricultural groups must be contacted by the project information officer. The experiment can be explained before it is launched. State experiment stations commonly serve as key information sources for most farmers in the state, and the ability to give an honest appraisal of rainfall modification is in the interest of the experiment stations. Their field men and communication channels are an essential way to reach citizens in the study area and those in the downwind areas.

A third group of non-local users to be informed before, during, and after the experiment are government officials. At the state level, this begins with the Governor's office. It would also include key staff in all departments affected by the experiment (agriculture, conservation, natural resources and/or insurance). As part of this activity, any state board or group that controls weather modification activities is to be informed about the project according to state, regulations. Copies of the Environmental Impact Statement can be distributed also and local area legislators should be routinely informed about the project.

At the federal level, all agencies providing support (direct or in direct) must be informed of all stages. An Environmental Impact Statement (EIS) must be prepared, filed, and approved before the project starts. An updated EIS should be filed at the start of the Area Experiment. The project activities will be routinely reported to NOAA (Department of Commerce) according to federal laws about weather modification. Presentations about the project should also be scheduled for the Interdepartmental Committee on Atmospheric Sciences, so that all federal agencies involved in weather modification will be kept aware of the project and its progress.

Another user group includes all the atmospheric, agricultural, and hydrologic scientists and engineers. The results of the project must be routinely presented and distributed to these user groups. Past experience has shown that scientific belief of the results reported for weather modification experiments are keys in developing scientific consensus that will support the effort. Key scientists in weather modification and cloud physics should be sought as advisors.

Special attention should be given to the exchange of information with the weather modification industry. They have major stakes in the field and will have a keen interest in HIPLEX. This group will ultimately be one of the main users of the proven technologies, and the project performance and results are of considerable importance to this industry. A suggested activity is for DAWRM to establish an advisory panel consisting of representatives from the weather modification industry, including officers of the Weather Modification Association and the North American Interstate Weather Modification Council. If done, it should be initiated in Phase 1 and continued through Phase 4 of HIPLEX.

B. Social, Economic and Environmental (SEE) Studies

These SEE studies actually involve three main activities as shown in Fig. 14. These include 1) use of numerical and conceptual models to study the social, economic and legal impacts and responses to any altered weather to quantify benefit/cost relationships and identify policy actions needed; 2) use of project site measurements and studies to provide data lacking in these models and to gather information lacking about environmental conditions; 3) extra-area measurements and studies to provide impact information.

The thrust of the SEE studies is twofold. One is to obtain results that serve as essential information to the local citizens and non-local user groups. The other goal is to provide results to set the experimental activities in the best possible framework. For example, environmental concerns involve the study area and the extra area, and they should include measurement of the impacts of the seeding material (silver), the impacts of the altered rainfall, and the impacts related to possible alterations in other forms of weather when rain is altered. A variety of ecosystem response studies are needed and index species must be identified.

The various activities recommended within the SEES framework appear in Table 2, identified under four headings: environmental, administrative-legal, social and economic. Under each heading, a set of activities is listed with each identified as being "essential" to HIPLEX or a "desirable activity" for HIPLEX. Hence, a priority is implied. Furthermore these activities are sorted by the four phases of HIPLEX so that the needs with time can be easily identified. The interaction between all the SEE studies is best viewed in Fig. 14 where they have been assembled according to modeling, on-site studies and extra-area measurements. Thus, topical and geographical views of SEES exist and must be kept in mind.

Administrative-legal tasks relate to keeping the project within a proper jurisdictional-legal framework. Social tasks largely involve monitoring of public attitudes. Economic tasks are the most extensive of the four topical areas. They involve modeling of benefits and losses from altered weather, cost assessments, and site and regional studies of responses.

A final activity of the SEES effort area (Fig. 14), in Phase 4, will involve designing the best possible measurement systems, the drafting of suitable regulations, and summarizing the economic aspects, all as input into the total design of an operational project.

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APPENDIX A

RECOMMENDATIONS FOR EXPLORATORY STUDIES

The design group of the Illinois State Water Survey provided the Division of Atmospheric Water Resources with recommendations concerning the exploratory studies needed for HIPLEX several times during 1975. These recommendations are reproduced in their original form in this Appendix in order to provide a convenient reference.

The first set of recommendations were in "task lists" in Sections IV and V of the document "Outline of Preliminary HIPLEX Plan", dated 30 September 1975. These task lists follow as the first of the set of reprints. The other recommendations, some of which were among the tasks listed in the outline of the preliminary plan, follow in chronological order.

I. Task lists, Sections IV and V of "Outline of Preliminary HIPLEX Plan", 30 September, 1975 pp. 11-20

IV. TECHNICAL EXPLORATORY STUDIES

The technical exploratory studies provide the background information needed for the . . . . . . seeding experiments . . . . Those relating primarily to the Phase II experiment (semi-Isolated, single cloud system) are shown diagramatically in Figure 2*. The bulk of these should be completed before going on to Phase II, although there is some overlap with the initial field effort in Phase II, which is devoted to testing.

A number of specific research "tasks" have been identified. These are shown diagramatically in Figures 3-8*. The reference in parentheses refer to the task list below in which they are given in greater detail.

Since many of the tasks address more than one component of the seeding experiment, they have been grouped into similar research areas.

This task list may include work which has already been done, or is underway. Every effort will be made to obtain detailed reports of all research which address these tasks.

A. Cloud and Precipitation Characteristics and Synoptic, Sub-Synoptic and Mesosynoptic Controls.

1. Precipitation Characteristics

Task 1:

Identify the precipitation climatologies required for establishing the essential statistical characteristics of the rainfall for the northern, central, and southern High Plains. Parameters such as areal cover, areal variability, diurnal variability, durations are of interest.

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*Figure 2 is now Figure 3 in Section II.C of this document.

**Figures 3-8 are now Figures 4-10 in Section Ill of this document.

Task 2:

Assemble the above statistics and make recommendations concerning hypotheses and operations (evaluation requirements are covered in C.2. below).

2. Cloud and cloud system characteristics

a. Cloud patterns and frequencies

Task 1:

Develop general radar climatologies, e.g., echo patterns, frequencies, movement, coverage, diurnal variation, from existing data. Availability and usefulness of data from the WSR-57 radar network should be investigated.

Task 2:

Develop systematic analyses of radar measurements, collected at the HIPLEX sites as the first step toward amassing background echo statistics for the three areas. Parameters of concern to hypothesis development (e.g., first echo heights), operations (e.g., dimensions), and evaluation should all be considered.

Task 3:

Determine relative frequency of unorganized shower clouds, organized squall lines, and larger rain-producing weather systems from satellite imagery.

Task 4:

Study initial, pre-rain cloud patterns and temporal development from satellite imagery where available.

b. Cloud structure and development

Task 1:

Review and synthesize existing literature on first echo and echo histories. Assess transferability of results from other areas to High Plains.

Task 2:

Identify critical radar measurements and develop radar analysis package for the description of life cycle of individual clouds and cloud systems.

Task 3:

Specify critical aircraft measurements needed for formulation and refinement of hypotheses for natural and modified precipitation formation.

Task 4:

Assess the utility of models for:

(a) increase of understanding of processes involved in cloud development and in the formation of rain,

(b) identifying influence of ambient atmospheric structure,

(c) test of modification hypotheses and prediction of outcome of planned intervention.

Identify critical measurements for feedback to model development.

Task 5:

Identify measurements and analyses by which precipitation efficiencies and/or productivities of individual clouds and cloud systems may be determined.

Task 6:

Assess need for supporting measurements (other than rainfall) e.g., surface and Upper air winds and temperatures, for adequate understanding of the forcing functions in cloud development.

3. Synoptic influence on cloud and precipitation characteristics

Task 1 :

Determine dependence of rainfall on frontal types.

Task 2:

Determine the dependence of cloud and precipitation formation on thermodynamic stratification and identify predictor variables which could be used in the evaluation of a seeding experiment. These may be determined from one-dimensional model calculations, or simple graphical operations on soundings.

Task 3:

Assess the adaptability of the ISWS objective surface diagnostic model to the High Plains. If warranted, make required modifications and generate surface kinematic, thermal, and dynamic parameters which may influence precipitation type and intensity. Determine dependence of precipitation on these parameters.

Task 4:

Develop "seedability" climatologies on the basis of available synoptic and meso-synoptic weather data.

Task 5:

Investigate importance of routine nuclei measurements (ice and/or CCN) at the surface and/or in the subcloud and cloud layer on the characteristics of precipitation. Assess the need for routine measurements.

B. Modification Hypotheses and Technologies

Task 1:

Critically review past weather modification programs, operational and experimental, for hypotheses, and technologies utilized and interpret results regarding these.

Task 2:

Identify all reasonable modification hypotheses and evaluate on the basis of supporting evidence of all types. Identify those applicable to High Plains cloud types and general High Plains climatology.

Task 3:

Evaluate various technologies on basis of status of development, past performance and logistic requirements.

C. Precipitation Measurement and Evaluation

1. Radar Measurement

An assessment of the capability of radar and particularly of the DAWRM 5-cm radar, to monitor rainfall from convective storms with an accuracy sufficient for the evaluation of weather modification experiments is urgently needed. This may be separated into two tasks.

Task 1:

Evaluation of Z-R relationships in general, and for the High Plains specifically.. The following specific studies are needed:

(a) Synthesis of existing Z-R relationships from the literature.

(b) Field research to include:

  (i) Thorough investigation of Z-R statistics using radar and raingage data collected at the three field sites, stratified by operational parameters, weather predictors, and type of rain or echo system.

  (ii) Comparison of radar Z with calculated Z derived from measurements of drop spectra at cloud base and middle level with the Knollenberg probes.

  (iii) Comparison of low-level radar Z with Z and rainfall rate calculated from surface raindrop spectrometer data.

In addition, the following studies would be very instructive.

(c) Assessment of Z-R relationships as indicated by comparison of relationships given by two nearly matched radars monitoring the same storm, e.g., analysis of Z-R using simultaneous CHILL (10-cm) and NCAR CP2 10-cm data.

Task 2

Evaluate the net effect of the 5-cm radar attenuation on estimation of rain and other cloud parameters (e.g. volume). The reasoning behind selection of the 5-cm radar is given in the DAWRM Preliminary Technical Plan. Estimated attenuation is given, in that report, but a recent report by Geotis indicates the attenuation problem may be more severe. Possible study approaches include:

(a) Specialized analyses of radar, raingage and aircraft measurements collected at the field sites.

(b) Studies based on concurrent measurements by 5~ and 10-cm radars.

2. Surface Measurements

Task 1:

Identify critical precipitation climatologies that need to be developed to design the evaluations of a) single, semi-isolated cloud seeding experiment; b) area-wide modification experiment covering all types of rain clouds; c) area-wide seeding experiment on wide-spread rain systems. This includes specifications of pertinent parameters, e.g., area averages, point rainfalls, rain intensities, etc.

Task 2:

Assemble the rain statistics identified in Task 1 and determine the raingage network characteristics (e.g., size, density, and configuration) and minimum gage capabilities needed for the evaluation of the three types of seeding experiments, for a) surface evaluation alone and b) a raingage/radar mix.

Task 3:

Assess surface network requirements for rainfall calibration of radar.

D. Operations

1. Facilities

Task 1:

Specify radar operations to allow efficient collection of data for chosen analysis goals, standardized at all sites within limitations of existing equipment.

Task 2:

Establish near real time data reduction procedures for raingage data needed for Z-R studies and radar calibration.

Task 3:

Consider the necessity for additional facilities at each site to cover functions other than primary data collection (e.g., aircraft guidance). Specify the types of facilities needed.

Task 4:

Establish rigorous calibration and maintenance procedures of all facilities to be followed at each location.

Task 5:

Design aircraft operations to accomplish the various objectives set out above, e.g., those connected with establishing radar capability, and/or cloud structure.

Task 6:

Evaluate adequacy of recently acquired aircraft systems and consider the need for strong aircraft. *This task should be given priority.*

Task 7:

Develop techniques for joint operations of regular and special facilities, e.g., aircraft, multiple radiosondes, etc.

2. Forecasting for Operations

Task 1:

If surface portion of ISWS extrapolated-diagnostic model was modified for High Plains, develop upper air section. Recommend forecast tests.

Task 2:

Assess the dependence of rainfall on large scale dynamic features, e.g., upper air short waves, thickness fields, air mass types.

Task 3:

Assemble calendar of weather events. Determine the percent of rain and other weather elements which occur in and out of severe weather watch boxes and determine degree of association between rain and actual severe weather events (tornadoes, floods, hail, etc.).

V. SOCIO-ECONOMIC AND PHYSICAL IMPACT STUDIES

As stated in the DAWRM goals (section I.A.), the research studies associated with the agricultural, economic, and social impacts are the main responsibility of the cooperating state agencies. However, any design document would be incomplete if it did not include a recognition of the importance of these impacts. Listed below are some tasks which should be addressed in the overall HIPLEX design. Those listed under C. will be dealt with in greater detail because of their direct effect on the implementation of the seeding experiment.

A. Agro-Economic

Task 1:

Identify gross agro-economic studies to be done over a sufficiently large part of the Great Plains and in sufficient areal detail to identify the economic value of modified rainfall in various regions.

Task 2:

Assess need for experimental plot studies to be carried out. Investigate if full scale experiments in one of the three regions, with small scale, very specialized studies elsewhere to permit the transferability of results is adequate.

Task 3:

Assess possibility of supplementing irrigation with resultant savings in dollars and groundwater.

B. Water Supply and Management

Task 1:

Study potential value of additional water in reservoirs and impact of this and additional rains on cost.

Task 2:

Determine need for hydrologic studies, as a requirement for properly specifying management of atmospheric water?

Task 3:

Investigate energy aspects of additional rain, e.g., energy saving due to decreased pumpage of ground water for irrigation water needs for energy generation.

C. Assessment of Potential Atmospheric Side Effects

Task 1:

Determine extra-area effects of the modification effort due both to advection of materials and to increased rainfall in the target area.

Task 2:

Assess probability that modification may produce undesired effects such as severe weather. Association between rainfall and undesired effects such as severe weather should be determined for historical period and then monitored during the project.

D. Social-Public Attitudes

Task 1:

Sample attitudes to get baseline data before seeding experiment starts.

Task 2:

Establish public relations mechanism. *This is urgent!*

II. Recommendations of the Illinois State Water Survey to the Bureau of Reclamation : 1975 HIPLEX Field Operations. June 16, 1975

A. General Recommendations

1. Establish liaison with operational seeding projects in each area. Arrange for receipt of operational logs, preferably in near real time. These logs should include in some detail the following:
    - a. When (date, times) seeding was done
    - b. Seeding technique utilized:
      Seeding agent, amount, how dispersed
    - c. Where seeding material was dispersed -
      particularly if in specific clouds.

   Since the operations in Kansas and Texas require State permit, the assistance of the State representative should be solicited.

2. Frequently the presence of silver in the rain water is suggested as a means of evaluating seeding. It would be wise to start determining the magnitude and variability in background silver. This should be done for one location in each of the three sites.

3. The 1975 summer period should be used to assess the usefulness of the more simple cloud models in predicting suitable cloud conditions for operations and in providing data sets suitable for model evaluation.

4. Vertical distributions (sounding) of ice and cloud condensation nuclei in lowest 10,000 ft should be obtained at beginning and ending of every operational day by the cloud base aircraft.

5. With unproven radars and radar processor it is strongly recommended that there be dedicated photographic backup recording. This will also provide a means for first look or fast scan for characteristic as of day.

B. Case analysis of 1975 field data for design purposes

These fall into two general types (1) those addressing the development of appropriate, scientifically sound, seeding hypotheses and (2) those addressing the evaluation problem - in particular the assessment of the capabilities of the project radars to provide a measurement of rainfall which is adequate for weather modification experiments. The former are based primarily in case studies of cloud and precipitation morphology, the latter on quantitative rain measurements and in cloud and precipitation drop spectra.

1. Cloud studies
    a. The level at which precipitation drop first form in cloud is informative of the dominant precipitation mechanism and/or of the timing of the precipitation mechanisms. The radars in all 3 regions should be operated continuously in a volume scan, with as close to 3 minute period as possible. The 3-minute period is preferred in order to provide comparable data to most of the first echo studies documented in the literature. At a minimum, the parameters to be documented are:
        1. Height and temperature of top of first echo
        2. Depth of first echo
        3. Whether or not the echo top height increased
        4. Maximum (Z) and level of maximum Z.

Some additional parameters which are desirable are:

1. Horizontal dimension of the first echo
2. Did it merge with an adjacent echo
3. Duration of echo - as an entity and as part of a complex
4. Maximum height attained, and the time between first appearance and maximum height

For design purposes these parameters should be shown as frequency distributions and as joint distributions, broadly stratified by pertinent synoptic parameters. These should be done for all three sites in order to infer differences in the dominant processes. Any clouds that could have been contaminated by operational seeding projects should be deleted.

b. Internal cloud properties must be documented both for the development scientifically sound hypotheses for natural precipitation development and for appropriate intervention. Critical aircraft measurements in the upper part of the cloud (0 to -8):

1. Estimates of updraft speed and area
2. Partition of condensate in updraft areas and in inactive or downdraft areas into three size groups: cloud particles, precipitation embryos, precipitation particles
3. Phase of the condensate, or at least existence of ice
4. Net buoyancy of updraft areas
5. Duration of updrafts in the cloud complex

Simultaneous measurements at cloud base:

1. Estimate of updraft speed, diminsion and continuity (i.e., is the updraft a single entity or is there a group of small disjointed updrafts)
2. Cloud base temperature and height

3. Buoyancy (or temperature anomaly) in the updraft area
4. Characteristics of the drop spectrum, in the updraft e.g., concentration, median volume diameter, number of precipitation embryos
5. Duration of the updraft

The upper and cloud base aircraft should be directed to the same cloud or cloud area, so that to the extent possible simultaneous measurements can be obtained at cloud base and in the 0 to -8° region. The observations should continue on the same cloud or cloud complex until the clouds dissipate. Three dimensional radar surveillance should continue throughout.

The analysis needed is determination. Characteristic values (medians, means, distributions) of the internal cloud parameters listed should be determined as a function of (a) age in the total cloud cycle, (b) cloud base temperatures, (c) maximum Z in the cloud at the time, (d) cloud top, (e) maximum rain fall rate determined for the cloud (if) evidence of ice. In addition the bulk quantities of the cloud condensate should be related to the adiabatic value as a reference value, to the characteristics of the drop spectrum at the cloud base and to the strength of the updraft.

c. Life cycles of storms and storm systems should be documented by the radar throughout the region and throughout the period of operation. This will permit extrapolation of aircraft-documented cloud characteristics to a larger population, as will as provide data for identification of similarities and differences between the three regions. First look measurements are:

top heights
maximum Z and heights of maximum Z

maximum volume or areal extent

duration of echo area

Further documentation would express these values as a function of time plus quantities such as shape parameters and mass.

These parameters should be considered in the context of the gross synoptic conditions and for general cloud system class such as areal percent coverage, scattered cloud, line echoes, echo clusters.

2. Radar evaluation of rainfall

   a. Documentation of Z-R relationships using aircraft spectra collected in rain shafts. Studies of the type done by MRI in Oklahoma should be carried out at all three sites. Whenever possible the base aircraft should be operated over raingages.

   b. Initiation of a study of raindrop spectra at the ground at all three sites, using raindrop spectrometers. This should be done at least one location in each region. Characteristics of the spectra e.g., the Marshall-Palmer parameters, characteristic Z-R should be determined as a function of cloud system type, location relative to rain case (from 0° radar scans) etc.

   c. Very little use of 5-cm radar to date and assessment of the capability of 5-cm radar for precipitation measurement must be done as soon as possible. The problems of attenuation is still very much an unknown. Non-field studies are indicated in recommendations for immediate studies to be undertaken.

The Miles City (5-cm) and North Dakota radars (5 -cm) are so situated that they have a common area of coverage. The dense Montana raingage network is in this area. High priority should be given to analysis of storms in the common area. Aircraft measurements, particularly in rain shafts or at base of raining clouds should be made whenever the opportunity exists. A raindrop spectrometer should be located in the common area. The analysis should stress initially at lease, the areal Z distribution of the 0° scans from the two radars.

III. Recommendations concerning interactions with the public for HIPLEX: October 1975.

PUBLIC INTERACTIONS FOR HIPLEX

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An essential part of HIPLEX concerns how the meteorological efforts (the background field studies and then the experiments) interface with the users and the public. Before the field efforts and experiments can be launched, a carefully presented program to inform the public about the project must be initiated. Past sociological studies generally point to a favorable public attitude towards weather modification experimentation prior to experimentation. These public attitude sampling efforts have revealed that for a complicated, difficult to understand science like weather modification, the majority of the public tends to depend on key local (township, city, and county) decision makers for opinion development. These decision makers vary and may include key farmers, bankers, clergy, mayors, elected county officials, extension agents, and conservation district directors. Thus, one major interactive-public relations effort concerns local (the people in and around the experimental area) users and interests.

In Phase I of this local interactive effort, the key people must be identified <u>in and around</u> the 2000 mi^2 area, and then systematically informed about all aspects of the experiment. Presentations to these small groups have to be honest and internally consistent. A short concise project information document should be developed for wide distribution. If reasonable, a "citizen's committee" could be developed as a focal point for a continuing interface throughout the project. A project information person is needed at all sites and times to give talks and to answer questions. Arrangements for temporarily stopping the experiment in adverse (generally, too wet) conditions need to be made.

The second phase of this local public interactive effort involves working with these local decision makers to develop a series of public presentations to key groups (service clubs, 4-H groups, farmer unions, etc.). The modification experiment should not be launched until Phases 1 and 2 are well initiated and a favorable and understanding local response is obtained. Among other things, this will aid in the local arrangements for instrument siting, a major effort.

The public in and around the area should be routinely and continuously informed through the news media about the progress of the project (Phase 3). The project forecast regarding experimental days could be aired over local radio stations, and summaries of annual results must be delivered to the public and to the local and state officials. All possible existing means for distributing information, such as the university extension services, should be used to distribute project information, both on a regular basis and about specific items of lay interest.

The other major interactive effort concerns related interest groups comprising the non-local users of the project results. One of these groups is the crop-hail and property insurance interests (companies and their associations). Successful weather modification could have a major impact on this industry, and they will wish to be closely informed of the progress and performance of the experiment. Further, their involvement is sought in the form of furnishing detailed daily loss data for the project area. Their endorsement of the experiment is also sought so that local insurance agents will understand the project and its potential value to them.

Another group of non-local users includes various agriculturalists at state universities, agricultural associations, the Farm Bureau, and major agri-businesses related to region agriculture. Hail suppression, if successful, would affect them in various ways. The strong influential reputation of the agriculture experiment station and agricultural associations also means they must be informed about the project so as to secure their understanding and to utilize their communication systems. Key officials in these agricultural groups must be contacted and the experiment explained before the experiment is launched. State experiment stations commonly serve as key information sources for most farmers in the state, and being able to give an honest appraisal of hail suppression is in the interest of the experiment stations.

A third group of non-local users to be informed before, during, and after the experiment are governmental officials. At the state level, this begins with the Governor's office. It would also include key staff in all departments affected by the experiment (agriculture, conservation, natural resources, and insurance). As part of this, any state board or group that controls weather modification activities is to be informed about the project according to state regulations. Also, local area legislators should be informed about the project.

At the federal level, all agencies providing support (direct or in-direct) must be informed of all stages, generally more often than grants or contracts require. The project activities will be routinely reported to NOAA (Department of Commerce) according to federal laws about weather modification. Presentations about the project should also be scheduled for the Interdepartmental Committee on Atmospheric Sciences so that all federal agencies involved in weather modification will be kept aware of the project and its progress.

Another user group includes all the atmospheric, agricultural, and hydrologic scientists and engineers. The results of the project must be distributed to these user groups. Specific attention should be given to the exchange of information with the weather modification industry. This group will be the main users of the proven technologies, and the project performance and results are of considerable importance to this industry.

IV. Recommendations concerning the critical precipitation climatologies needed for single cloud and area seeding experiments. 13 October 1975.

CRITICAL PRECIPITATION CLIMATOLOGIES
NEEDED FOR
DESIGN AND EVALUATION
OF
SINGLE CLOUD AND AREA SEEDING EXPERIMENTS

Floyd A, Huff
and
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The climatologies needed for design and evaluation of the single cloud (ie. complex of several cloud elements or convective entities separable from other complexes) are different than those needed for the area seeding experiment. For the single cloud evaluation, the most probable design is the paired storm design in which one member of the pair is selected at random to be seeded, and the other member is designated to be the control. The tracking of single clouds in time and space to a sufficient degree of accuracy requires 1) a dense network, 2) a very accurate and sophisticated 10-cm radar system, or 3) a combination of the dense network and radar systems. Otherwise, many of the entities will go undetected, and the measurement of interest, precipitation on the ground produced by these entities, cannot be measured properly.

Apparently, the dual use of a dense network and 10-cm radar system was quite useful in evaluating the Florida seeding experiments. However, the HIPLEX radar system is 5-cm and testing for a dual raingage-radar system has not been performed for the 5-cm system. Also, in order to satisfy the agricultural interests of the high plains, it is desirable that an accurate measurement of the *actual rainfall reaching the ground be determined.* Thus, it would appear that the optimal method of detecting single cloud rainfall is through the use of a dense raingage network. Since it is impractical to operate a dense network for a sufficient period of time prior to the single cloud proof-of-concept experiment, it is recommended that the 2,000 mi^2 METROMEX recording raingage network of 1 gage/9 mi^2 be used to develop the essential climatologies needed for determining the density, size, and placement of gages, as well as the design and evaluation. It is recognized that the climatology of the High Plains is different from that of the Midwest. However, both areas include similar rain and synoptic types. The major climatological differences are most likely to occur in the frequency distribution of rain and synoptic types, Thus, for a given rain and synoptic type, the measurement requirements should be similar. Estimate of experimental duration can be adjusted according to the proportion of storms or days in each rain or synoptic type in the High Plains seeding areas. If 1976 is a non-seeded year, the establishment of a dense network on the scale of the METROMEX network would provide information on the reliability of estimates made from the METROMEX data.

For the area seeding experiment, the most likely candidates are the crossover design or random-experimental design with predictor variables. Certainly, the experimental areas will most likely be larger in the area seeding experiment than in the single cloud experiment and both upwind and downwind areas must be considered. For this phase of experimentation, a dense network of the METROMEX type may be impractical over the larger area. However, if the daily mean rainfalls are the important ground measurements of interest, then a less dense network over a large area is an acceptable alternative. Also, at this stage of experimentation (ie, completion of the single cloud experiment), a determination of the adequacy of rainfall measurements from a combination of 5-cm radar and raingages should have been accomplished.

In the meanwhile, it is considered important that certain precipitation climatologies be performed over various areas to obtain critical information for design and evaluation purposes. For these studies, it is recommended that precipitation climatologies be performed for unit areas of 2,000 mi^2 upwind, in, and downwind of the HIPLEX sites. The choice of a 2,000 mi^2 unit area is based on climatic variability and the desirability of comparisons between areas of the same size as the METR0MEX network. These climatologies would be derived from daily rainfall data from the National Weather Service (NWS) cooperative stations. A detailed listing of the desirable climatologies for the single cloud and area seeding experiments is included below.

Single Cloud Experiment

1. Climatology of the standard error of the areal mean rainfall for various areas (500 mi^2, 1000 mi^2, 1500 mi^2, and 2,000 mi^2) and various raingage densities (METR0MEX data).
2. Climatology of the area sizes needed to sample the complete life histories of single cloud storms (METR0MEX data).
3. Climatology of the variances of rain parameters (volume, area, duration, path length, etc) of single cloud storms (raincells, METR0MEX data).
4. Climatologies of the covariance between single cloud rainfalls (raincells, METROMEX data).
5. Climatology of diurnal rainfall distribution for selected points (NWS hourly rainfall data, from High Plains),
6. Climatology of storm duration for selected points (NWS hourly rainfall data from High Plains),

7. Climatology of hourly rainfall according to synoptic type and precipitation type (NWS data from selected points in the High Plains).

8. Climatology of areal extent of storms stratified by storm intensity (NWS rainfall data from High Plains plus METROMEX data).

9. Climatology of storm movements.

Area Experiment

1. Climatology of daily rainfall distributions (amount and frequency) by months (May, June, July, August, and September) for unit areas and selected points (NWS daily rainfall data in the High Plains).

2. Climatology of daily rainfall distributions (amount and frequency) by seasons (June-August and May-September) for unit areas (NWS daily rainfall data for the High Plains).

3. Climatology of the covariances between the unit areas (NWS daily rainfall data from High Plains).

4. Climatology of the covariances between unit areas and nearby sounding variables (NWS daily precipitation data and B of R sounding data).

5. Distribution of daily rainfall data according to synoptic and precipitation types (NWS daily rainfall data and SWS synoptic data from the High Plains).

6. Climatology of monthly and seasonal rainfall in the unit areas and selected points (NWS daily or monthly data).

7. Relation between severe weather distributions (TRW, hail, heavy rain) and total rainfall distributions.

8. Comparison of daily rainfall distributions during wet, dry, and moderate periods—monthly and seasonal comparisons.

9. Distribution of sequences of wet and dry days.

Estimates of variability necessary for the statistical sampling requirements for the single cloud, cross-over, and random-experimental design with predictor variables would be derived from the above listed climatological information. The use of covariates is viewed as an all important method for reducing the natural rainfall variability. Studies of covariances between unit areas and sounding variables, as well as on-going studies of physical models, should be explored in regard to predictor variables. Also, the capability of the 5-cm radar to measure rainfall on the ground should have been demonstrated by the time of the area experiment, and this information should be considered along with the rainfall climatologies in the design and evaluation of the area experiment.

V. Suggestions for developing climatologies of the cloud conditions in the High Plains. 24 October 1975.

MEMORANDUM

TO: Dr. B. Silverman *DATE:* October 24, 1975

FROM: Dr. Bernice Ackerman

SUBJECT: Suggestions for cloud climatologies

Some information on cloud climatologies is available in the CSU report and Haragan's thesis. Some of what follows below is patterned after their work. However, neither report stratified the distributions for rain and no-rain cases and this is felt to be a critical factor to be considered. We have summarized some general climatologies that would be helpful in formulating the hypotheses, designing the experiment, and designing the evaluation scheme. Basically, what is sought are the frequency of isolated shower clouds (which determines the number of opportunities per time unit) and some information about their characteristics.

As you can see below, there is a large number of tabulations that can be done, and it is difficult to say which will be the most definitive. The most (and least) critical are obvious however.

Since the WABAN tapes carry a lot of other useful information, we have suggested some supplementary climatologies that would be useful. I suggest you discuss this task with Arlin Super. He did some precipitation-type climatology for Montana (I have a barely decipherable copy).

1. <u>Stations</u>: Miles City, Goodland, Big Springs if available, or Midland.

   <u>Season</u>: April (or May?) through September. (If winter experiment is anywhere in long range plan, then it may be worthwhile to do full year. Design interest is only in April-September growing season.)

   Period of <u>Record</u> : 10 years at <u>least</u>, representativeness of period, as far as mean rainfall should be checked. Period when <u>hourly</u> (rather than 3-hourly) data are available would be preferred, but also latest such 10 years (1955-1964).

2. Cloud <u>types</u>: Similar to grouping by Haragan for Texas:

   i. Cumulus
   ii. Cumulonimbus and Cb mama

iii. Sc (and Fc)
iv. St (and Fst)
v. Ac
vi. Acc
vii. As and Ns
viii. Ci
ix. Cs, Cc

Note: if in combined categories, both cloud types are recorded in the same hour, it should only count as one occurrence not two.

3. Basic frequency distributions (number of occurrences of each cloud type) stratified as indicated in later items. Frequencies expressed as 1) number of occurrences, 2) fraction of total numbers of possible occurrences, 3) average, maximum and minimum number of occurrences in each cell.

a. For each cloud type, frequencies

- i. as a function of hour and month, f_{ij} where i = hour, j = month
- ii. f_{ij} summed over "convective" period, and all other hours, where convective period is defined 1100 to 2200 LST, incl. (You may want to get some input from your field directors on limits for this period).

b. For Cu and Cb, frequency of each in association with

- i. each of other cloud types (coverage of other cloud types 4/10 or more, or (second choice),
- ii. other cloud types grouped according to middle (types v, vi, vii), high (viii and ix), low (iii and iv) with total cover 4/10 or more.

c.

- i. Average coverage for each cloud type as a fraction of hour and month
  $\sum_{d} C_{i,j,d}$ where d = days in a month (e.g., there are 30 observations at 0100 for each June in the sample).
- ii. average minimum and maximum coverage for each cloud type for "convective" as defined above and all other hours.

d. Special tabulations for Cu and Cb, (types i and ii) taken separately -- not grouped together.

- i. Frequencies (hour and month) stratified by amount (of own type) for categories (in tenths) 0-3; 4-6; > 7.
- ii. frequency distributions of time of first observation on a day, by month.

111. average, maximum and minimum height of base, by hour and month..

4. Stratifications

a. First level — by day,

i. Rain or no-rain on day

ii. Maximum rain fall in any hour on day:

no rain	<.01 in
light	(.01 - 0.10 in)
moderate	(0.11 - 0.50 in)
heavy	(over 0.50 in)

*iii. Rainy hour average (i.e., rain for day divided by number of hours with rain)

*iv. Rainy hour average for convective period (rain/number of hours with rain in convective period).

b. Second level -.- within rainy day

1. Cloud conditions for the hour prior to the onset of precipitation preferably for each rain event where rain event defined as unbroken period of precipitation, preferably from hourly rainfall tape. Frequency of occurrence of each cloud type, but at least Cu, Cb in association with other types (3.b. above). Cloud height for low cloud layer.

Stratified by month

Maximum hourly precipitation (categories as in 4.a. in rain event)

Duration of rain event

11. Within rainy day, each hour stratified by rain amount (categories in 4.a.) for tabulations given in 3 (Tabulations for no-rain days should have come out in 4.a.)

111. Stratification by wet, dry, and normal months and by wet and dry seasons, where wet and dry are defined as being above and below the normal, resp. These are given in annual climatological summaries. The 'season' can either be the full six months and/or some portion of the six months (e.g., May-August).

5. Weather categories -- frequencies and stratifications.

Thunderstorm rain (T alone, TRW, A)

* Need to get frequency distributions of these quantities to determine categories.

B. Showery rain (RW)

C. Stratiform rain with embedded convective elements (TR)

D. Continuous rain (R, L)

E. All frozen precipitation except hail

a. Frequency of occurrence of each weather category by hour and month.

b. For the two weather categories, T alone and T, RW together and RW, Δt = I-R frequency of At where At is hour of first report of the weather category minus the hour of beginning of rain event.

c. Stratified by first weather category reported and/or by weather category of maximum intensity, the cloud conditions prior to onset of precipitation (4.b.).

d. Stratification as in c, frequencies of wind direction in hour prior to onset of rain.

6. Wind direction

a. Frequency of occurrence of wind direction for each weather category

b. Frequency of occurrence of wind direction one hour prior to onset of precipitation, stratified by weather category, initial and maximum in rain event.

c. Contingency table of rain event duration vs wind direction one hour prior to onset.

7. Precipitation and weather category

a. Hourly precipitation vs weather category (see Super's report)

b. Distribution, duration of rain event (hourly records) or of continuous weather, by month.

c. Distribution of amount of rain in rain event.

Note: We are really interested in cloud base temperatures. It would be desirable therefore to express the distributions of cloud height in terms of temperature, at least for Cu, Cb classes. Possible method (useful only during "convective" period as defined aboveX assume some fraction of dry adiabatic lapse rate (e.g., 0.8?) in sub-cloud layer and calculate temperature at cloud base height from surface temperature.

VI. Recommendations for priority analysis of 1975 field data: 20 November 1975.

MEMORANDUM

TO: Bernie Silverman DATE: 11/20/75

FROM: Bernice Ackerman

SUBJECT: HIPLEX

I. PRIORITY ANALYSIS FOR DESIGN

The analyses listed below are needed by late March 1976 for development of the HIPLEX design. In view of the shortness of time, we have identified more or less crude looks at the radar and aircraft data to provide first estimates of cloud characteristics. *This list is not intended to preclude more sophisticated and complete analyses of the data either concurrently or at a later date.* Obviously, the more complete the information about the natural cloud development, the more definitive the design and experiment.

It is believed that the analyses indicated below can be completed within two or three months.

A. RADAR CLOUD CHARACTERISTICS: STATISTICS OF ECHO SIZES, TOPS, AND SPACING.

For one volume scan every half hour, identify all individual echo clouds at 1 km above cloud base (or -5C, if easier to determine from available data), where echo cloud is specified by closed 10 dbz (?) contour. These should be done from a CAPPI if possible or for variable elevation angle as a function of range. (The reflectivity level for defining the cloud is not firm. An appropriate value should be decided upon in conference with Klazura and field operators and should reflect the characteristics of the radar clouds).

1. For the individual radar clouds so defined, determine
    - a. area
    - b. dimensions (e.g. major and minor axes)
    - c. separation (distance to next radar cloud, edge-to-edge)
    - d. height and temperature of top (if more than one turret, highest only)
    - e. peak reflectivity and height and temperature at which it occurred
    - f. number of high intensity cores (single or multicellular).
2. For the area of coverage
    - a. description of echo array (e.g. line, scattered, cluster, large clouds and satellites, etc.)
    - b. total number of cells
    - c. coverage

Data should be stratified by:

- type of synoptic pattern;
- cloud base height, temperature (estimated if necessary);
- other ambient conditions, e.g. temperature, dewpoint, precipitable water, etc, to give idea of larger scale conditions.

B. FIRST ECHO CHARACTERISTICS, BASE AND TOP TEMPERATURES.

These are most valuable for identification of natural precipitation processes. This study requires a time consuming effort but even fragmentary data from all three locations would be most valuable.

C. AIRCRAFT MEASUREMENTS: CLOUD CHARACTERISTICS.

1. Cloud physics aircraft
   - a. total water content and partition of condensate into cloud particles, precipitation embryos, precipitation particles, in the updraft areas.
   - b. phase of condensate or at least existence of ice and whether ice form is crystal or pellet.
   - c. estimates of updraft speed and width of updraft.

   These should be accompanied by the following information:
   - height and temperature of the traverse and height above cloud base if available;
   - whether cloud was single or multiple cell;
   - cloud top if known;
   - whether cloud was isolated or a member of a group.
2. Cloud-base aircraft
   - a. cloud base temperature and heights (outside of rain shaft if any)
   - b. estimates of updraft speeds, dimensions and whether continuous
   - c. drop spectra in updrafts (e.g. concentration, number of precipitation embryos, median volume diameter).

D. RADAR/AIRCRAFT RAINGAGE MEASUREMENTS.

1. Z-R studies should be carried out.
   - a. radar-aircraft disdrometer studies, of the type done by MRI in Oklahoma
   - b. radar-raingage and aircraft disdrometer — raingage studies for as many well documented situations as possible. These should concentrate on days on which there is data for several rains and for a sample of days covering different intensity rains.

2. A supplementary approach to Z-R would be to use area-depth calculations, if any suitable cases exist (Huff, 1968)*, that is, correlate rainfall area-depth to area-depth determined from radar integrations.

3. Attenuation

   Radar data for Enterprise radars should be scanned for evidence of attenuation.

   a. "notching" in echoes
   b. missing echoes in known rain areas

E. RAINFALL CLIMATOLOGIES

(Refer to document "Critical Precipitation Climatologies" and transmittal letter dated October 13).

1. Climatology of hourly rainfall according to synoptic type and precipitation type from NWS data. (ISWS is doing pilot study of areal mean daily rainfall according to synoptic type.)

2. Climatology of storm movements.

II. URGENT STUDIES FOR HIPLEX

Listed below are recommendations of research efforts which are considered urgent. These have been covered previously in documents to the Bureau. They are listed here to bring them to your attention.

A. ATTENUATION AND RELATED QUESTIONS IN 5-cm RADARS.

1. Studies utilizing two 5-cm radars observing the same storm from different vantage points should be undertaken as soon as practicable. The obvious place to start is with the Montana and North Dakota radars. The comparisons should be made with all due account being taken for the problems of ground echo and radar horizon, probably by working at elevation angles of a degree or more. We understand from Dr. Simpson that results of similar 5-cm studies made in GATE should be available soon. These results should be obtained and critically studied.

2. Every effort should be made to carry out as soon as possible studies of simultaneous measurements at 5~ and 10-cm wavelengths, analogous to the study reported by Geotis. Potential situations for doing this exist in NHRE, South Dakota, at NSSL, or in Texas

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*Huff, F. A., 1968: Area-Depth Curves - A useful tool in weather modification experiments. <u>JAM</u>, Vol. 7, 940-943.

B. DEVELOPMENT OF RADAR-CLOUD CLIMATOLOGIES (from existing historical data).

These data are available from NWS WSR-57 for Big Springs and the Goodland area but NWS did not have any coverage over Montana. Possible data banks for Air Force bases *should be investigated.*

The following analyses should be performed. (Some already have been done for western Kansas by Bark.) These should be related to area rain.

1. Frequency of occurrence of echo for every hour, or more often if regularly available, as a function of
   - a. geographical location (sub areas of coverage area)
   - b. time of day
   - c. month or season
   - d. type of day (in terms of
     - i. rainfall
     - ii. synoptic type
     - iii. hail-no hail
     - iv. surface T, T_d).
2. Frequency of occurrence of echo motions (speed and direction) as a function of items a) through d) above.
3. Frequency of occurrence of new cell developments as a function of a) through d) above.
4. Frequency of occurrence of echo top heights as a function of a) through d) above. (ISWS has ordered radar logs from Asheville and will be doing some of this to satisfy design needs.)
5. Frequency of occurrence of echo pattern types (such as lines, scattered areas) in sub-areas of the area of coverage. Relate to synoptic types, rainfall.
6. Frequency of occurrence of percent echo coverage in sub-areas of the area of coverage.
7. Size distributions and durations of individual echoes as a function of synoptic conditions.

APPENDIX B

STATISTICAL DESIGN

This section of the report deals with the statistical design and evaluation of the "single cloud" experiment, where the term "single cloud" is extended to include a complex composed of several cloud elements or cells but which is *separable from other complexes.* it deals with the randomization scheme, the statistical methods, and the sampling requirements. Lacking a suitable clfmatological base for the High Plains, METROMEX rain data were used to arrive at some of the recommendations. These should be modified as necessary as radar, rain, and other cloud data for the experimental sites are amassed and analyzed.

1. Basic Design Considerations

a. Randomization, experimental unit, and sampling unit.

There are conceivably three randomization schemes that could be employed in the Single Cloud Design. These are 1) randomization between days, 2) randomization between storms*, and 3) randomization between single clouds*. Since the experimental unit is defined to be the unit to which the treatment is applied (Steele and Torrie, 1960), the choice of randomization also determines the experimental unit. However, the effect of the treatment is measured on the sampling unit, which can be some fraction of the experimental unit or the entire experimental unit (Steel and Torrie, 1960). Thus, if 'between-day' randomization is chosen, the experimental unit is the day and the sampling unit is the single cloud. If 'between-storm' randomization is chosen, the experimental unit is the storm and the sampling unit is the single cloud. If 'between-c1oud'randomization is chosen, the experimental unit and the sampling unit are the same — the single cloud.

Since a single cloud design is being considered, it would seem logical to propose that the experimental unit be the individual cloud. If the single cloud were the experimental unit, then the randomization could be 1) between the members of paired clouds, or 2) between individual unpaired clouds. For the paired cloud design to be effective, the pair must be chosen so that the members of the pair have the same characteristics and occur at the same time, or at nearly the same time. On an operational basis, these conditions are extremely difficult, if not impossible, to fulfill. Consequently, the paired cloud design is rejected.

The option of randomization between unpaired clouds is also rejected. Results of tracer studies (Semonin, 1973) indicate that considerable transfer of tracer material occurs between clouds in multicellular convective systems. These results led Semonin to conclude that a target control design for advertent

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* The "single cloud" is defined as a comples of convective element, visually distinct and separable from other complexes, at least in the middle and upper levels. A storm is defined as a group of such clouds, visually separable but close enough to each other so that the whole is viewed as an area of cloudiness. Each single convective complex which rains produces one or more identifiable raincells at the ground, but neither the rain nor the cloud development can be considered entirely free of possible influence of neighboring cloud complexes.

weather modification in a multicellular convective system is unsound unless the target and control are separated by at least 20 miles.

Another reason for rejecting the single cloud as the experimental unit lies in the operational difficulties in recognizing the single cloud or cloud complex prior to treatment. The difficulties are accentuated by the general lack of agreement on how to define a single cell. Is it to be determined by radar or by visual inspection of the pilot? What reflectivity line is to be used? The current HIPLEX procedure for cell identification (post-season analysis) is to collapse an area of rainfall, from the surface to the highest elevation tilt, onto a single "B-scan" plan view. The cell is then defined in plan view by a constant reflectivity line (10 or 20 dbz) , although information concerning the "inner cores" (35 dbz) is also retained. However, it is obvious that an arbitrary definition of the cell can cause problems for subsequent analysis of physical effects of seeding.

Herein lies the difficulty of using the single cell for the experimental unit: the delineation of the cell in a particular way "locks" the statistical and physical analyses into rigid experimental units, which later analyses and understanding may show to be improper. That is, the *a priori* statistical inferences will be linked to one cell definition and treatment, and other statistical inferences will necessarily have to be of the *a posteriori* type. This difficulty is partially circumvented if the experimental unit is declared to be the storm or the day, while selecting the cell or single cloud to be the sampling unit. It is then possible to define the cell (the sampling unit) in a variety of ways without seriously affecting the statistical inferences. That is, there will be greater flexibility in testing physical hypotheses, and errors in cell recognition from the operational standpoint will not be so serious.

Another strong reason for rejecting the single cloud as the experimental unit is that the seeded cloud may "merge" with an unseeded cloud, and the definition of the experimental unit itself is then in jeopardy. Mergers occur quite often (Simpson, et al., 1973; Changnon and Huff, 1975) and, in fact, the role of mergers in enhancing precipitation was one of the basic concepts in the Florida experiments by Simpson, et al., (1973). Certainly, the testing of a "merger" hypothesis is severely restricted if the experimental unit is the single cloud. (i.e., randomization and treatment between clouds).

If the cell is rejected as the experimental unit, then should the storm or the day be used as the experimental unit? Recent arguments have favored the use of the day or a subset of the day as the experimental unit (Flueck, 1975). The advantages of using the day to be the experimental unit according to Flueck, are 1) it meaningfully handles the diurnal cycle, 2) it provides an opportunity to estimate mesoscale effects, 3) it allows for some nighttime seeding, and 4) it presents a convenient operational unit.

Conversely, Schickedanz and Huff (1971) have shown the desirability of using the storm as the experimental unit when one has a dense raingage network in the target area. One of the major advantages of using the storm as the experimental unit is that one can meaningfully determine the synoptic "type", which is often not possible if the experimental unit is defined to be the 24-hour period. The dominating force in determining rainfall characteristics of a storm are the large-scale weather conditions, and it is quite conceivable that seeding effectiveness will vary substantially with synoptic conditions. Therefore, using the storm as the experimental unit removes an extraneous source of variation which, in turn increases the precision of the experiment.

Another strong reason for not using daily or 24-hour rainfall as the experimental unit is the bias introduced in comparing seeded and non-seeded samples. Seeding usually involves an operation during only a portion of the day, such as 6 to 8 hours in the afternoon and evening. The seeding is then only effective in the target for part of the day, and the seeding effect is diluted (underestimated) when seeding-no seeding comparisons are made for 24-hour periods during which additional rainfall may fall in the experimental area.

On the other hand the use of the storm as the experimental unit may be criticized on the basis of problems associated with definition and contamination. The problem of defining the storm in the single cloud experiment is minimized because the system needed to adequately measure single cloud rainfall can also be used in delineating the storm. The contamination problem can be minimized either by requiring a buffer period or buffer zone or by skillful stratification of the storm during the analysis stage into categories or potentially contaminated storms and those storms for which contamination was unlikely.

Moreover, since the goal of the single cloud experiment is to increase the rainfall from single clouds and is not necessarily to increase the areal storm rainfall, it is not deemed necessary to seed nighttime clouds. (Certainly, in the areal experiment where the purpose is to determine changes in the rainfall over the target area, nighttime seeding may be necessary to provide an adequate sample of the organized rain-producing situations.) In addition, the use of the storm eliminates the necessity of "prescreening" the experimental unit. Flueck (1975) indicates that the motivation for prescreening generally comes from two sources: 1) desire for homogeneity of experimental units, and 2) economic constraints. We believe that this homogeneity can be achieved by specifying the synoptic weather situation when the storm is used for the experimental unit so that only post-screening (partitioning of the data with predictor variables, etc., after the fact) is required.

There is another distinct advantage in using the storm (or the day) as the experimental unit as opposed to the cell. The storm rainfall can be totaled for the seeded and non-seeded cases and a statistical test between the seeded and non-seeded storms totals can be applied, in addition to a test between seeded and non-seeded cells. This provides a natural tie-in to the area experiment and affords the opportunity to conduct the single cloud experiment in conjunction with exploratory phases of the area experiment. If definitive predictor variables can be found for storm rainfall, there is hope that a potential increase in storm rainfall due to single cloud seeding may be detected in a reasonable period of time. Research involving a search for areal or storm predictor variables is the subject of Appendix C.

We believe that the advantages of using the storm as the experimental unit far outweigh any disadvantages associated with its use, and it is concluded that *the experimental unit for the single aloud experiment should be the storm, provided it can be adequately defined for the High Plains, and identified in real time, and the sampling unit should be the individual cloud (cell).*

In this scheme, the randomization would be conducted in the following manner. The storm (experimental unit) is delineated as it approaches the network, or as it initiates on the network. The storm would be identified in real time by airborne scientists in radio communication with the radar. The entity must be clearly recognizable to both the airborne scientist by eyeball and the radar scientist as an isolated echo or close group of echoes. If the storm is designated to be a seeded storm, all cells selected as good candidates during the life of the storm are to be seeded. The cloud physics aircraft monitors the cells selected by collecting pertinent physical measurements. If the storm is designated to be a non-seeded storm, cells are selected in the same manner as if they were to be seeded, and the cloud physics aircraft monitors the storm system as before. (This is necessary to provide a valid control sample for the experimental design).

There is the possibility that a second storm might approach the network or initiate in another part of the research area while the first storm is still being seeded and/or monitored. Two options are available: (l) if additional seeding aircraft were available, this new incoming storm system would be a new experimental unit, or (2) such storms would automatically be classified as unseeded storms and would be used in the subsequent analyses as a special stratification. The adoption of option (1) would provide another set of data which, although cloud physics measurements would be unavailable, would provide a wealth of data for evaluation based on the radar and dense raingage information.

A final point concerning randomization: Its purpose in the weather modification experiment is to assure an unbiased estimate of experimental errors and/or treatment means and the differences between them (i.e., randomization tends to destroy the correlation among errors). To avoid bias in the comparison of the treatment (seeded and non-seeded means), it is considered necessary to have a way of assuring that the seeding cases will not be consistently handicapped by some extraneous sources of variation, known or unknown (Steele and Torrie 1960).

In order to achieve this admirable goal, the concepts of grouping, blocking, and balancing should be considered. Grouping is defined as the placement of the experimental units into different groups so that they can be subject to treatment (seeding) (Ostle, 1963). This is accomplished by the randomization procedure itself. Blocking means that the experimental units are allocated so that the units within a block are relatively homogeneous (Ostle, 1963). This concept would be useful when a certain synoptic regime persists for several days. In order to properly account for the persistence, it may be necessary to group the storms (experimental units) into equal seeded and non-seeded samples (balancing) in each block. That is, blocking and balancing is an attempt to assure that the treatment is adequately "spread"over differing meteorological regions. Flueck (1975) suggests that variable blocks of units (in this case, storms) might be used which would have an equal number of seeded and non-seeded units (perhaps 2, 4, 6, or 8 experimental units).

The advantages of the proposed statistical design can best be illustrated by the various options available for comparisons of seeded and un-seeded samples. These include, among other possibilities; 1) comparisons between seeded and non-seeded cells, 2) comparisons between collections of seeded and non-seeded cells, and 3) comparisons between seeded and non-seeded storms.

In regard to the first group of comparisons, it is recognized that the cells (sampling units) are correlated with each other within the experimental unit. This correlation may be allowed for in two ways. First, the cells can be stratified according to the degree of correlation. The amount of correlation can be considered as a reflection of the physical nature of the storm system (i.e., isolated cells versus imbedded cells, air mass situation versus squall line, etc.). Thus, the stratification according to correlation can provide physical insight for the evaluation. Secondly, the second and third groups of comparisons do not involve correlations between cells; consequently, valid comparisons are available, while pertinent and useful cell information is retained.

For the second group of comparisons, there can be any number of cell collections. For example, Simpson and Woodley (1975) and Woodley and Sax (1976) used the "floating target", which is a collection of all seeded clouds (cells) and those that merge with them. Obviously, any collection of cells used will be a floating target. Another possible collection of cells would be the seeded cells and all those that are within a specified distance of the seeded cells. Comparisons between seeded and non-seeded collections stratified according to distance would provide an excellent method of testing for extra-area effect on the cloud scale. Furthermore, any of these collections can be compared to cells not seeded during the storm for within-experimental-unit controls. However, caution should be exercised due to the possibility of inter-cloud contamination.

In the third group of comparisons, the characteristics of the storm are compared. In this regard, the total rainfall depth of the storm, the areal size of the storm, the duration of the storm, and the number of cells in a storm are examples of the parameters that might be compared in this group. In this way, the effect over the area can be assessed as well as the effect on individual single clouds and the experiment can be considered as a form of an "area" experiment. However, this is not the "true" area experiment which will be performed in Phase 3; it will treat complex systems of cumuliform clouds as well as the simple, semi-isolated entities. *The physical mechanisms are different, and the "true" area experiment must not begin until an acceptable level of statistical and physical certainty is obtained in the Single Cloud experiment.*

In addition, other comparisons can be envisioned. For example, clouds which have a complete set of data measurements(i.e. cloud physics measurements, radar measurements, and ground rainfall measurements) could form a special class of comparisons. Another class would consist of those which have only radar and rainfall measurements, or those which have only rainfall measurements. Clearly, several classes of comparisons are available based on the quality and quantity of data. Consequently, the proposed statistical design provides an opportunity to make valid statistical comparisons, as well as the opportunity to use physical information and deduction in conjunction with the statistical design.

These choices of experimental units, sampling units, etc. presuppose that reasonable detection times can be achieved and that the different physical analyses and interests can be satisfied by such a design. In the sections to follow we will show that both of these conditions can be satisfied by the skillful application of discriminant analysis to the design and evaluation problem, and by the development of the appropriate relationships for determination of power of the test.

b. Statistical methods

The choice of the storm as the experimental unit leads to a design which has been designated as the random-experimental design (Schickedanz and Changnon, 1970, 1971; Schickedanz and Huff, 1971). This design does not incorporate historical data, and the evaluation is based strictly on data obtained during the experimental period. The total number of units needed to obtain significance for a specified difference and level of precision is given by Schickedanz and Changnon (1970) as

$$N = \frac{(\mu_\alpha + \mu_\beta)^2 \sigma^2}{D^2 \pi (1-\pi)} \qquad (1)$$

where: μ_α = the normal deviate for α probability level

μ_β = the normal deviate for β probability level

D = the difference in means it is desired to detect

Σ^2 = the variance of the non-seeded sample (assumed to be equal to the seeded variance)

π = the randomization factor (equal to 1/2 for a 50-50 randomization)

If the data are log-normally distributed, σ^2 is the log-transformed variance and D is equal to the logarithm of $(1+\delta)$ when an increase is being tested (6 is the percentage difference it is desired to detect on the non-transformed scale). In order to apply the equation, an estimate of the log-normal variance is needed prior to the experimentation.

If the experimental unit is the individual cell, Equation 1 is totally appropriate for the purpose of estimating sample sizes for individual cells. It is not strictly applicable when the cells are sampling units instead of experimental units because of the correlation between the sampling units within the experimental unit. However, the use of a test comparison between cells, when used in conjunction with the comparisons between collections of cells and storms, offers a way to reduce scientific uncertainty. Thus, the use of Equation 1 to estimate sample size for the sampling units and the use of the corresponding 2-sample test for evaluation purposes in the experiment provides useful and pertinent information.

Even so, it is noted that the application of a univariate statistical test to a particular cell parameter has its limitations. Such a test has the distinct disadvantages of not utilizing the information contained in the other cell parameters and, in some cases, overestimating or underestimating the importance of a particular parameter. It is far superior to provide a multivariate test, whereby the information in all of the cell parameters can be utilized. For example, all seven parameters listed in Tables 7 and 8 of part 2 of this Appendix could be used in the computation of the test statistic. The use of discriminant analysis can provide the appropriate multivariate test statistic in this case. The method has been successfully applied by Schickedanz (1974) to discriminate between characteristics of raincells exposed to differing urban and industrial influences. This technique is especially appropriate for the Single Cloud experiment since the storms are separated into randomized groups while the cell parameters represent the effect-components of interest.

The discriminant analysis will also provide a measure of which cell characteristic is the most important parameter with regard to distinguishing potential differences between seeded and non-seeded cell characteristics. The most important advantage is that the discriminant function can include characteristics not only of the radar echo (echo base ht, echo tops, area of the cloud base, etc.) but also the cloud physics measurements and characteristics of individual surface raincells. *This permits a tie-in between the physical events within the clouds and the rainfall that reaches the surface from these clouds. In this sense, the discriminant function provides a set of predictor variables for single clouds which can be used to remove extraneous sources of variation, thereby increasing the precision of the experiment.* All that is required is that a complete set of measurements be available for the variables of interest for each experiment unit. Obviously, some variables will not be available for each experimental unit, and therefore, different discriminant functions and stratifications will be required depending on the quantity and quality of data. For example, clouds which have a complete set of data measurements (i.e., cloud physics measurements, radar measurements, and ground rainfall measurements) could form a special discriminant function. Another discriminant function could consist of data which have only radar and rainfall measurement, and still another of data which have only rainfall measurements. Clearly, several discriminant functions can be formed based, on the quality and quantity of data.

In order to estimate the sampling requirements for the multivariate test between cloud characteristics of seeded and non-seeded storms, a method to estimate the power of the test is needed. This can be done in the following manner.

First, we consider p cell variates (i.e., some combination of radar, cloud, and surface cell characteristics) namely v1, V_2, . . . v_p, which are of interest on both the seeded and non-seeded experimental units (storms).

The p × p covariance matrix, C_s, and the p x p covariance matrix, C_n, are computed where the subscripts s and n denote the seeded and non-seeded groups, respectively. The within-groups sum of squares p × p matrix, W, is then computed by:

$$W = (n_s - 1)\ C_s + (n_n - 1)\ C_n \tag{2}$$

where n_s denotes the number of seeded observations (experimental units) and n_n denotes the number of non-seeded observations (experimental units).

The observations from the seeded and non-seeded experimental units are then combined to form an overall group of observations for the p variates. The p x p covariance matrix, C, is then computed for the overall group. The total-group sum of squares matrix, T, is then computed by:

$$T = (n-1)\ C \tag{3}$$

where $n = n_s + n_n$. The between-group sum of squares is then computed directly by:

$$B = T - W \tag{4}$$

In order to discriminate between the seeded and non-seeded groups, we desire that the between-group sum of squares, B, be large with respect to the within-groups sum of squares, W. In particular, it is desired to maximize the ratio of B to W. This can be accomplished by computing the eigenstructure of the $W^{-1}B$ matrix through the following equation:

$$(W^{-1}B - D)\ E = 0 \tag{5}$$

If the matrix $W^{-1}B$ were symmetric, E would be the p x p matrix consisting of a set of orthonormal eigenvectors of $W^{-1}B$ as the columns and D would be the standard p × p diagonal matrix of the eigenvalues (λ) of $W^{-1}B$. However, it is noted that although $W^{-1}B$ is the product of two symmetric matrices, the product itself is nonsymmetric (Cooley and Lohnes, 1971). Thus, special methods of computing the eigenstructure of a nonsymmetric matrix must be used instead of the methods normally used to compute the symmetric eigenstructure (Cooley and Lohnes, 1971).

In addition, B is of reduced rank, and since the rank of a matrix product is always the same as that of the smaller of the matrix ranks composing the product, the rank of $W^{-1}B$ is also reduced and is the same as that of B. B is not of full rank whenever g-1 (g is the number of groups) is less than p, in which case the rank is exactly g-1 (Cooley and Lohnes, 1971). In the Single Cloud experiment, there are only two groups (seeded and non-seeded); therefore, the rank is one. If the rank equals 1, the implication is that only one eigenvalue can be extracted from Equation 5. The eigenvalue maximizes the ratio W"lB, and its associated eigenvector is called the discriminant function.

The discriminant function is a vector of weights and, for the Single Cloud application, the weights represent the p cell variates (i.e., radar, cloud, and surface raincell characteristics). The "loadings" of these variates on the discriminate function yield a measure of the most important cell characteristics in differentiating (discriminating) between seeded and non-seeded groups (storms). For example, it is conceivable that one of the cloud characteristics measured by the cloud physics aircraft will be the most important in discriminating between the seeded and non-seeded clouds. The advantage of the application of discriminant analysis is that it will judge each cell characteristic and then use all this information to test between the seeded and non-seeded experimental units (storms).

The statistic for the discriminating power between the seeded and non-seeded groups is given by Wilk's Lambda, Λ, and can be computed by:

$$\Lambda = \frac{1}{1 + \lambda} \tag{5}$$

since there is only one eigenvalue, λ, associated with the seeded and non-seeded groups. A X^2 test for significance is given by:

$$\chi_p^2 = -\left(n - \frac{p+g}{2} - 1\right) \ln \lambda \tag{6}$$

with degrees of freedom ndf = (p) (g^{-1}). Since g=2, ndf reduces to p, the number of cell variates.

Clearly, if the seeded and non-seeded samples are available, Equations 2-6 can be used to test for the differences between the seeded and non-seeded storms and to assess the role of each parameter in discriminating between storms. However, for design purposes, an estimate of the sampling requirements to obtain a given level of precision is needed. We now turn our attention to this problem. First, we solve Equation 6 for n, obtaining:

$$n = \frac{p+g}{2} + 1 - \frac{\chi_p^2}{\ln \Lambda} \tag{7}$$

In order to obtain a proper estimate of the required sample size, n, it must be determined how large x_D^2 must be to provide a power probability (i.e., 1-β) of obtaining a value of X^2 significant at the a probability of the null distribution. Since the test statistic is distributed as X_p^2 the power of the test against a specific alternative can be approximated by (Schickedanz and Krause, 1970):

$$\text{Power} = P(\Delta) = \text{Prob}[\Delta > \chi_p^{2'}(\alpha)] \tag{8}$$

where $\chi_p^{2'}$ (a) is the value of the non-central chi square corresponding to the a level of significance. The power obviously depends on A, the non-centrality parameter. Therefore, A can be estimated through the use of the non-central chi square distribution, χ_p^2 (a). Fix (1954) has computed tables of the non-central chi square for the .05 and .01 size of the test and for power levels of .1, .2 . . . .9. In these tables, A is the tabled value corresponding to values of P(A) and p. In order to obtain the proper values of X^2 to use in Equation 7, it will suffice to enter the desired power level for a specified a in the tables, and the value of A for specified degrees of freedom can then be obtained by interpolation. The value of A obtained in this manner is used for X^2 in Equation 7. For power levels exceeding .9, the tables of Johnson and Pearson (1969) can be used.

In order to use the above relationships, an estimate of A must be determined from climatological data. This estimate is obtained by increasing the sample values of the distribution of cell parameters by various pre-determined amounts. This provides a series of "seeded" distributions for various combinations of pre-determined increases on the cell parameters. The discriminant analysis (Equations 2-6) is then performed on the original (non-seeded) distributions and the "seeded" distributions to obtain an estimate of A. Now, with this value of A associated with a specified combination of cell increases and the value of $X_p^2 = \Lambda$ obtained from the tables of Fix, the sample size, n, needed for a particular combination of cell parameter increases can be computed from Equation 7.

c. Sampling Requirements

In order to develop the particulars of the statistical design and establish sampling requirements, a climatological data base of surface raincells and radar cells determined by the 5-cm radar system are needed. Unfortunately, such a climatological data base is unavailable, although it is hoped that the analyses of the 1975-76 field data will serve to fulfill at least part of this need. For the time being, METROMEX rain data from the period 1971-1973 have been used to obtain approximations needed for estimating some of the requirements of the statistical design as well as for determining the density, size, and placement of gages. The METROMEX data base is composed of 2786 raincells from 181 storms which occurred during June-August over the 3-year period and were delineated in the manner described by Schickedanz (1973, 1974) and Schickedanz and Busch (1975).

It is recognized that the surface raincell distribution can only serve as a first estimate and guide, since the raincell frequency is less than the frequency of seedable convective clouds. Furthermore, it is likely that the radar will show a greater frequency of "cells" than will the raingage network. In fact, the frequencies of radar echoes will probably be different from clouds frequencies also. Obviously, analyses similar to these being employed with the METROMEX raincells should be repeated for the radar and rain data obtained during the summers of 1975 and 1976. The analyses of these summer data from the High Plains will serve to firm up the estimates from the METROMEX data. Also, sampling size requirements for collections of cells and storms should be estimated; however, this is best done with the summer data from the 1975-76 field operations.

The estimated sampling requirements for HIPLEX will be discussed in detail in part 4 of the Appendix, following a description of the results of the METROMEX analyses which were done to arrive at these estimates.

II. Climatology of Cell Sampling and Area Coverage

An important issue in the single cloud experiment is the number of cells that can be sampled with a raingage network of varying sizes. The METROMEX network, which covers an area of about 2,000 mi^2 (5180 km^2) and has a raingage density of 9 mi^2(23.3 km^2)/gage, was subdivided into areas of 1500, 1000, and 500 mi2 (3885,2590, and 1295 km^2). The number of cells with complete life histories within the four networks so defined was then determined (Table B-1). The number of complete raincell histories on a 1295 km^2 network is 22.7% of the number on a 5180 km^2 network for this 3-year period. The percentage of "complete" cells increased to 55.5% on a 2590 km^2 network and jumped to 85.6% on a 3885 km^2 network (where the number on the largest network is used as the base).

Another important issue is the number of storms that can be sampled with a rain network of varying sizes and the amount of areal coverage that will be obtained from each respective network size. The number of storms that were sampled with varying amounts of areal coverage according to year is listed in Table B-2 for the 1295 and 2590 km^2 networks.

For the overall 3-year period, 24.3% of the storms on the 5180 km^2 network were not detected on the 1295 km^2 network and 12.2% of the storms were not detected on the 2590 km^2 network. Furthermore, only 48.1% of the storms on the 5180 km^2 network cover greater than 20% of the 1295 km^2 network and only 50.8% of the storms cover greater than 20% of the 2590 km^2 network. The number of storms not detected in a given year ranged from 10.6% to 30.4% on the 1295 km^2 network and from 2.1% to 16.9% on the 2590 km^2 network.

For air-mass storms, 45.1% (23 of 51) were undetected on the 1295 km^2 network (Table B-3). Only 3.6% of the squall line storms and 9.3% of the squall area storms did not appear on the 1295 km^2 network. Furthermore, 92.9% of the squall line storms and 72.1% of the squall area storms had greater than 20% coverage on the 1295 km^2 network. When the network was expanded from 1295 km^2 to 2590 km^2, the percentage of undetected storms decreased for the majority of the synoptic types. For air-mass storms, this percentage was decreased by a factor of 2, and for the squall-area storms the same percentage was decreased by a factor of 4 (Tables B-3 and B-4).

III. Sampling Models

As mentioned previously, there were 2786 raincells* during June-August over the period 1971-1973. However, this is not a realistic number of cells

"The terms "storm" and "cell" as used in connection with the METROMEX data are defined as follows:

Raincell: a raincell in a multicellular system is a closed isohyetal entity within the overall enveloping isohyet of the rain-producing system; that is, it defines an isolated area of significantly greater intensity than the background rainfall. When raincells develop apart from a multicellular storm system, there is no background rainfall and the single cell is uniquely defined by the separation between rain and no rain. For details, the reader is referred to Schickedanz (1973, 1974) and Schickedanz and Busch (1975).

Rainstorm: an entity of rain (1 or more cells and/or areas of rain) on the network that can be identified with a specific synoptic weather classification and is separated from other entities by 20 miles and/or 1 hour between end and start times.

Table B-1 Comparison of the number of raincells sampled by networks of varying sizes (METROMEX 1971-73 data).

	Size of network area (km.^{2})			
Synoptic Type	1295	2590	3885	5180
	Number of ceells			
Air Mass	45	111	158	178
Squall Line	264	624	944	1117
Squall Area	167	401	633	740
Stationary Front	34	82	138	156
Cold Front	50	146	230	273
Warm Front	22	74	115	130
Post-Stationary Front	14	20	39	42
Post-Cold Front	15	36	49	57
Pre-Warm Front	7	20	34	38
Pre-Cold Front	7	14	18	19
Low	8	19	30	31
Unclassified	0	0	3	5
Ail Types	633	1547	2391	2786
	Percent of the cells sampled in the 5180 km^2			
Air Mass	25.3	62.4	88.8	100.0
Squall Line	23.6	55-9	84.5	100.0
Squall Area	22.6	54.2	85.5	100.0
Stationary Front	21.8	52.6	88.5	100.0
Cold Front	18.3	53.5	84.2	100.0
Warm Front	16.9	56.9	88.5	100.0
Post-Stationary Front	33.3	47.6	92.9	100.0
Post-Cold Front	26.3	63.2	86.0	100.0
Pre-Warm Front	18.4	52.6	89.5	100.0
Pre-Cold Front	36.8	73.7	94.7	100.0
Low	25.8	61.3	96.8	100.0
Unclassified	00.0	00.0	60.0	100.0
All Types	22.7	55.5	85.8	100.0

Table B-2 Areal coverage of the 1971-1973 METROMEX storms on the 1295 km^2 & 2590 km^2 networks according to year.

1295 km^2 network

Year	=0%	> 0	>20	>40	>60	>80	=100	Total number of storms on 5180 km^2 network
			Areal		Percent		Coverage	
1971	5	42	27	24	18	12	6	47
1972	21	48	29	22	16	15	10	69
1973	18	47	31	26	24	15	7	65
1971-73	44	137	87	72	58	42	23	181

Percent of total number of storms

Year	=0%	> 0	>20	>40	>60	>80	=100
1971	10.6	89.4	57-5	51.1	38.3	25.5	12.8
1972	30.4	69.6	42.1	31.0	23.1	21.7	14.5
1973	27.7	72.3	47.7	40.0	36.9	23.1	10.8
1971-73	24.3	75.7	48.1	39.8	32.0	23.2	12.7

2590 km network

Areal Percent Coverage

	=0%	> 0	>20	>40	>60	>80	=100
1971	1	46	31	25	19	12	4
1972	10	59	31	20	16	12	6
1973	11	54	30	26	22	13	5
1971-73	22	159	92	71	57	37	15

Percent of total number of storms

	=0%	> 0	>20	>40	>60	>80	=100
1971	2.1	97.9	66.0	53.3	40.5	25.6	8.5
1972	14.5	85.5	44.9	28.8	23.0	17.3	8.7
1973	16.9	83.1	46.2	40.0	33.8	20.0	7.7
1971-73	12.2	87.8	50.8	39.2	31.5	20.4	8.3

Table B-3 Areal coverage of the 1971-1973 METROMEX storms on the 1295 km^2 network according to synoptic type.

	Areal Percent Coverage							
Synoptic Type	=0%	> 0	>20	>40	>60	>80	=100	Total number of storms on 5180 km^2 network
Air Mass	23	28	5	3	0	0	0	51
Squall Line	1	27	26	24	22	18	14	28
Squall Area	4	39	31	25	21	16	6	43
Stationary Front	3	8	4	4	3	2	1	11
Cold Front	7	12	8	7	5	3	2	19
Warm Front	1	6	4	4	4	2	0	7
Post-Stationary Front	0	3	2	1	0	0	0	3
Post-Cold Front	4	7	3	2	1	0	0	11
Pre-Warm Front	0	1	1	1	1	1	0	1
Pre-Cold Front	0	2	1	0	0	0	0	2
Low	0	4	2	1	1	0	0	4
Unclassified	1	0	0	0	0	0	0	1
All Types	44	137	87	72	58	42	23	181

	Percent of total number of storms						
	=0%	> 0	>20	>40	>60	>80	=100
Air Mass	45.1	54.9	9.8	5.9	0	0	0
Squall Line	3.6	96.4	92.9	85.7	78.6	64.3	50.0
Squall Area	9.3	90.7	72.1	58.1	48.8	37.2	14.0
Stationary Front	27.3	72.7	36.4	36.4	27.3	18.2	9.1
Cold Front	36.8	63.2	42.1	36.8	26.3	15.8	10.5
Warm Front	14.3	85.7	57.1	57.1	57.1	28.6	0
Post-Stationary Front	0	100.0	66.7	33.3	0	0	0
Post-Cold Front	36.4	63.6	27.3	18.2	9.1	0	0
Pre-Warm Front	0	100.0	100.0	100.0	100.0	100.0	0
Pre-Cold Front	0	100.0	50.0	0	0	0	0
Low	0	100.0	50.0	25.0	25.0	0	0
Unclassified	100.0	0	0	0	0	0	0
All Types	24.3	75.7	48.1	39.8	32.0	23.2	12.7

TableB-A Areal coverage of the 1971-1973 METROMEX storms on the 2590 km^2 network according to synoptic type.

	Areal Percent Coverage							Total number of storms on 5180 km^2 network
Synoptic Type	**=0%**	**> 0**	**>20**	**>40**	**>60**	**>80**	**=100**	
Air Mass	11	40	6	3	0	0	0	51
Squall Line	1	27	27	24	22	17	11	28
Squall Area	1	42	32	25	20	15	1	43
Stationary Front	2	9	6	4	3	2	1	11
Cold Front	4	15	8	7	6	3	2	19
Warm Front	1	6	4	4	4	0	0	7
Post-Stationary Front	0	3	2	0	0	0	0	3
Post-Cold Front	1	10	3	2	0	0	0	11
Pre-Warm Front	0	1	1	1	1	0	0	1
Pre-Cold Front	0	2	1	0	0	0	0	2
Low	0	4	2	1	1	0	0	4
Unclassified	1	0	0	0	0	0	0	1
All Types	22	159	92	71	57	37	15	181

	Percent of total number of storms						
	=0%	**> 0**	**>20**	**>40**	**>60**	**>80**	**=100**
Air Mass	21.6	78.4	11.8	5.6	0	0	0
Squall Line	3.6	96.4	96.4	85.7	78.6	60.7	39.3
Squall Area	2.3	97.7	74.4	58.1	46.5	34.9	2.3
Stationary Front	18.2	81.8	54.5	36.4	27.3	18.2	9.1
Cold Front	21.1	78.9	42.1	36.8	31.6	15.8	10.5
Warm Front	14.3	85.7	57.1	57.1	57.1	0	0
Post-Stationary Front	0	100.0	66.7	0	0	0	0
Post-Cold Front	9.1	90.9	27.3	18.2	0	0	0
Pre-Warm Front	0	100.0	100.0	100.0	100.0	0	0
Pre-Cold Front	0	100.0	50.0	0	0	0	0
Low	0	100.0	50.0	25.0	25.0	0	0
Unclassified	100.0	0	0	0	0	0	0
All Types	12.2	87.8	50.8	39.2	31.5	20.4	8.3

on which to base an estimate of sampling requirements for the single cloud experiment. Clearly, the aircraft cannot seed and/or adequately measure the physical characteristics of all of the clouds which complete their life histories within the research area. Thus, two sampling models were assumed in order to obtain background samples needed to base an estimate of sampling requirements for the design of the single cloud experiment. These models are referred to as Sampling Models #1 and #2.

In Sampling Model #1 the following selection procedure was used to obtain a sample of cells consistent with the probable operational procedures. First, it was assumed that the operations would be limited to daylight hours (0600-2000) and only those cells that occurred during these hours were considered for the experiment. Secondly, it was assumed that the center of operations was at the center of the network. It was then assumed that, if at the beginning of a storm, two or more cells initiated simultaneously on the network, the first cell to be selected by the seeding aircraft would be the cell closest to the center of operations and within the network. The aircraft then followed the subject until it dissipated. A time period of 15 minutes was then allowed to elapse to permit the aircraft to make a second selection. This selection was the first cell to initiate after the 15 minute elapsed period; if more than one initiated at the same time, the cell closest to the location where the first one dissipated was chosen. Selections for the third, fourth, etc. were made in a similar manner. This selection procedure yielded a sample of 4l4 cells from the total population of 2786. The number of storms with a given number of cells is listed in Table B-5. The average number of cells per storm was 2.9 while the median number of cells per storm was only 1.7.

Sampling Model #2 was hypothesized because of possible complications that might arise when one attempts to select clouds (cells) located within a larger rain system. The complications include:

1) The contamination of one cell by another — if one cell is downwind of, or close (within 10 km) to, another cell, the two may not be independent of each other. In a test of cloud seeding, independent clouds (cells) are preferred.

2) The relatively weak cells which initiate when a rain system begins to break down -- scattered areas of light precipitation (0.10 in/hr or less) become the rule when a large-scale rain pattern weakens. These areas of light rain, although raincells by definition, would probably be poor candidates for seeding. These cells are dying and usually last for short periods of time.

Sampling Model #2 was designed to minimize the above problems. It was again assumed that the operations would be limited to daylight hours (0600-2000). It was also assumed that imbedded cells (i.e., those that initiated imbedded in an existing system) and dissipating cells would not be included. The first cell selected by the seeding aircraft was the cell that initiated closest to the center of operations within the network. The aircraft then followed the selected cell until it dissipated, and a period of 15 minutes

Table B-5 The number of cells per storm, using Sampling Model #1 (METROMEX 1971-1973 data).

	Number of storms with the given number of cells												Total number of storms
Year	0	1	2	3	4	5	6	7	8	9	10	11	
1971	1	12	4	5	6	1	2	2	1	0	1	0	35
1972	7	18	11	5	4	7	0	4	0	3	0	1	60
1973	6	9	13	5	3	4	6	1	0	1	0	0	48
1971-73	14	39	28	15	13	12	8	7	1	4	1	1	143

Percent of the total number of storms

1971	3	34	11	14	17	3	6	6	3	0	3	0
1972	12	30	18	8	7	12	0	7	0	5	0	2
1973	13	19	27	10	6	8	13	2	0	2	0	0
1971-73	10	27	20	10	9	8	6	5	1	3	1	1

Table B-6. The number of cells selected during each storm for the Single Cloud design using Sampling Model #2 (METROMEX 1971-73 data).

	Number of storms with the given number of cells									Total number of storms
Year	0	1	2	3	4	5	6	7	8	
1971	3	16	4	9	1	1	1	0	0	35
1972	12	18	13	9	2	4	1	0	1	60
1973	6	11	15	4	6	4	2	0	0	48
1971-73	21	45	32	22	9	9	4	0	1	143

Percent of the total number of storms

1971	9	46	11	26	3	3	3	0	0
1972	20	31	22	15	3	7	2	0	2
1973	13	2?	31	8	12	8	4	0	0
1971-73	14	32	23	15	6	6	3	0	1

was then allowed to elapse in order to permit the aircraft to make the second selection. The cell selected would be the first one to initiate after the 15 minute elapsed period; if more than one cell initiated at the same time, the cell that initiated the farthest upwind from the first sample cell was selected. If none of the cells initiated upwind, the cell that initiated at the greatest distance from the preceeding cell was chosen. Selections for the third, fourth, etc. were made similarly. This procedure yielded a sample of 288 cells.

The following important differences between Sampling Models #1 and #2 should be noted: 1) Sampling Model #2 is based on selecting the cell farthest upwind from the previous cell instead of the cell closest to the previous cell, as was done in Sampling Model #1 (this minimizes the contamination problem), 2) no dissipating cells (those that formed from the breakdown of a system of light rain) were considered in Sampling Model #2, and 3) no imbedded cells (those that initiated within a system of rain) were considered in Sampling Model #2.

The number of storms with a given number of cells for Sampling Model #2 is listed in Table 6. The average number of cells selected per storm was 2.0 and the median number of cells selected per storm was only 1.2.

The log-normal distribution was fitted to the 414 cells selected by Sampling Model #1 and the resulting goodness-of-fit probabilities (G. F. P.) are listed in Table 7 along with the characteristics of the cells. If one uses the often-cited .05 level of significance, the parameters of mean rain and maximum rain* are log-normally distributed, whereas volume is nearly log-normally distributed. The parameters of area, duration, maximum area** and minimum rain* do not follow the log-normal distribution.

A good measure of the relative sensitivity of a parameter in relation to potential increases from seeding can be obtained by a comparison of the mean and standard deviation. The smaller the standard deviation is in relation to the mean, the greater the sensitivity. The more sensitive parameters will also have smaller log standard deviations than the less sensitive parameters. Thus, at least in the Ill-Mo area, the parameters of area, duration and maximum area should have greater degrees of sensitivity than the other parameters (the maximum area will have the greatest degree of sensitivity).

The log-normal distribution was also fitted to the 288 cells selected by Sampling Model #2 and the resulting G. F. P. are listed in Table 8 along with the statistical characteristics of the cells. Again, the parameters of mean rain and maximum rain are log-normal whereas volume is nearly log-normal. The parameters of area, duration, maximum area, and minimum rain do not follow the log-normal distribution.

It is noted that the log standard deviations are lower for the raincell parameters of Sampling Model #2 than for the parameters of Sampling Model #1 (Tables 7 and 8). This is a direct reflection of the fact that the large imbedded cells are not in Sampling Model #2. However, this does not imply

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*Max rain (min rain) is defined to be the largest (smallest) average rainfall for a 5-min period during the life history of the cell.

**Max area is defined to be the largest 5-min areal size during the life history of the cell.

Table B-7. Characteristics of the raincells selected by Sampling Model #1

Raincell Parameter	Mean	Standard Deviation	Log mean	Log Standard Deviation	G.F.P.
Volume (hectare-m)	20.38	56.04	1.39	1.73	.03
Mean rain (mm)	2.06	3.53	-.14	1.31	>.20
Area (km^2)	63.71	62.36	3.84	.74	<.01
Duration (min)	27.90	24.50	2.96	.90	<.01
Maximum rain (mm)	1.42	2.99	-.84	1.62	.10
Maximum area (km^2)	45.32	30.81	3.65	.54	<.01
Minimum rain (mm)	.30	.63	-2.40	1.45	<.01

Table B-8. Characteristics of the raincells selected by Sampling Model #2

Raincell Parameter	Mean	Standard Deviation	Log-normal mean	Log-normal Standard Deviation	G.F.P.
Volume (hectare-m)	17.13	55.24	1.22	1.58	.03
Mean rain (mm)	1.86	3.65	-.20	1.18	.12
Area (km^2)	55.13	54.55	3.72	.69	<.01
Duration (min)	30.43	25.67	3.06	.89	<.01
Maximum rain (mm)	1.21	3.10	-.96	1.47	>.20
Maximum area (km^2)	41.83	28.67	3.58	.51	<.01
Minimum Rain (mm)	.11	.23	-2.87	.97	<.01

that these cells will require less time to verify since a smaller number of these cells are sampled each year. This point will be discussed further in subsequent sections.

IV. Sampling Requirements Estimated for a Single Cloud Experiment

a. Fifty-fifty randomization

The number of cells necessary to obtain significance for various percentage increases at the .50, .70, .90, and .95 power $(1-\beta)$ levels were computed by applying Equation 1 and using the log-normal estimates of σ^2 for the raincell parameters (Tables B-7 and B-8). The average number of cells obtained per year during the 3-year period was 138 from Sampling Model #1 and 96 from Sampling Model #2. These average numbers were used to convert the number of cells to the *number of years** required for detection of a percent increase in a parameter. The results from Sampling Model #1 are listed in Table B-9, while the results from Sampling Model #2 are listed in Table B-10.

In order to have a 95% chance (power) of detecting a 60% increase in cell volume for Sampling Model #1 (Table B-9), 4.2 years are required. However, a 60% increase will be detected 70% of the time in just a 1.8 year period. Maximum area is the most sensitive parameter since there is a 70% chance of detecting 1) a 20% increase in maximum area in 1.2 years and 2) a 10% increase in 4.4 years. The sampling requirements are all greater for Sampling Model #2 (Table B-10) than for Sampling Model #1 except for the minimum rainfall parameter.

An inspection of Tables B-9 and B-10 reveals that different numbers of years are required to detect increases for the different parameters. Thus, it is possible that the discriminant approach could reduce the overall sampling requirements since it uses information from all parameters jointly, rather than testing each parameter individually. However, it is not adequate to merely increase each parameter by an arbitrary amount in the discriminant function. Arbitrary increases in one parameter may not be realistic when compared to arbitrary increases in another parameter. For example, the results listed in Table 10 indicate that it takes less time to detect a 20% increase in area than in volume. However, what are the chances of obtaining a 20% increase in area as compared to volume?

To obtain a realistic comparison, the increases for the discriminant function were obtained by first computing the standard error of the mean, S_m, for each parameter:

$$S_m = S/N^{\frac{1}{2}} \qquad (9)$$

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*In the discussion that follows sample size refers to the number of years, assuming sampling units numbering 138/yr and 96/yr for Sampling Models #1 and #2 respectively.

Table B-9. Comparison of sample size requirements (years) for various raincell parameters for the Single Cloud design for Sampling Model #1 (non-discriminant approach, a=.05)

		Sample size required for differences of:				
Parameter	Power	5%	10%	20%	40%	60%
Volume	.50	97.5	25.6	7.0	1.0	<1.0
	.70	169.1	44.3	12.1	3.6	1.8
	.90	309.1	81.0	22.1	6.5	3.3
	.95	389.9	102.2	27.9	8.2	4.2
Mean Rain	.50	56.2	14.7	4.0	1.2	<1.0
	.70	97.4	25.5	7.0	2.0	1.0
	.90	178.0	46.6	12.8	3.7	1.9
	.95	224.6	58.9	16.1	4.7	2.4
Area	.50	17.8	4.6	1.3	<1.0	<1.0
	.70	30.8	8.1	2.2	<1.0	<1.0
	.90	56.3	14.8	4.0	1.2	<1.0
	.95	71.0	18.6	5.1	1.5	<1.0
Duration	.50	26.3	6.9	1.9	<1.0	<1.0
	.70	45.6	11.9	3.3	<1.0	<1.0
	.90	83.3	21.8	6.0	1.8	<1.0
	.95	105.0	27.5	7.5	2.2	1.1
Maximum Rain	.50	85.8	22.5	6.1	1.8	<1.0
	.70	148.8	39.0	10.7	3.1	1.6
	.90	272.0	71-3	19.5	5.7	2.9
	.95	343.1	89.9	24.6	7.2	3.7
Maximum Area	.50	9.6	2.5	<1.0	<1.0	<1.0
	.70	16.7	4.4	1.2	<1.0	<1.0
	.90	30.5	8.0	2.2	<1.0	<1 .0
	.95	38.5	10.1	2.8	<1.0	<1.0
Minimum Rain	.50	69.1	18.1	4.9	1.4	1.0
	.70	119.8	31.4	8.6	2.5	1.3
	.90	219.0	57.4	15.7	4.6	2.4
	.95	276.3	72.4	19.8	5.8	3.0

Table B-10. Comparison of sample size requirements (years) for various raincell parameters for the Single Cloud design for Sampling Model #2 (non-discriminant approach).

Parameter	Power	Sample size required for differences of: 5%	10%	20%	40%	60%
Volume	.50	118.0	30.9	8.4	2.5	1.3
	.70	204.6	53.6	14.6	4.3	2.2
	.90	374.0	98.0	26.8	7.9	4.0
	.95	471.8	123.6	33.8	9.9	5.1
Mean Rain	.50	65.2	17.1	4.7	1.4	<1.0
	.70	113.2	29.7	8.1	2.4	1.2
	.90	206.9	54.2	14.8	4.4	2.2
	.95	261.0	68.4	18.7	5.5	2.8
Area	.50	22.5	5.9	1.6	<1.0	<1.0
	.70	39.0	10.2	2.8	<1.0	<1.0
	.90	71.2	18.7	5.1	1.5	<1.0
	.95	89.9	23.6	6.4	1.9	1.0
Duration	.50	37.4	9.8	2.7	<1.0	<1.0
	.70	64.9	17.0	4.6	1.4	<1.0
	.90	118.6	31.1	8.5	2.5	1.3
	.95	150.0	39.2	10.7	3.2	1.6
Maximum Rain	.50	102.0	26.7	7.3	2.2	1.1
	.70	177.0	46.4	12.7	3.7	1.9
	.90	323.5	85.0	23.2	6.8	3.5
	.95	408.1	107.0	29.2	8.6	4.4
Maximum Area	.50	12.4	3.2	1.0	<1.0	<1.0
	.70	21.5	5.6	1.5	<1.0	<1.0
	.90	39.4	10.3	2.8	<1.0	<1.0
	.95	49.7	13.0	3.6	1.0	<1.0
Minimum Rain	.50	44.1	11.6	3.2	<1.0	<1.0
	.70	76.4	20.0	5.5	1.6	<1.0
	.90	139.7	36.6	10.0	2.9	1.5
	.95	176.3	46.2	12.6	3.7	1.9

where S is the standard deviation and N is the number of cells in the sampling model (414 for Sampling Model #1 and 288 for Sampling Model #2). The percent increase is then determined on the probability of the mean value exceeding its standard error. That is, the mean will exceed 1 standard error 66.6% of the time, 2 standard errors 95% of the time, etc. If we let C_e be the number of standard errors and X be the mean value, then the percentage increase is given by:

$$\text{Percent increase} = (\bar{X} + C_e\, S_m)\ 100/\bar{X} \qquad (10)$$

The C_e values of 2.0, 3.0, 4.0, and 8.0 were then applied to each cell parameter and the corresponding percent increases were determined. The determination of the increase in this way provides a realistic comparison between parameters, since each parameter's increase has been based on its variability. (Since the volume is equal to the mean times area, the percent increase for volume was determined from the product of the increased mean and area parameters.) By using these increases, all sample values ("non-seeded" values) were increased to form "seeded" values. The discriminant analysis was then applied to the "seeded" and "non-seeded" values to provide the required values of A. Equation 7 was then used to obtain estimates of the sampling requirements for the various power levels at the .05 level of significance, and the results for Sampling Model #1 are listed in Table B-ll as the discriminant combination. The percent increases for each parameter are indicated in parentheses next to the .50 power values.

For a discriminant combination of percent increases in volume, mean rain, area, duration, maximum rain, maximum area, and minimum rain of 43, 25, 14, 13, 31, 10, and 31, respectively, there is a 70% chance of detection in 3.3 years. In order to have a 90% chance of detection, 5.1 years would be required. For percent increases in the discriminant combination of 59, 34, 19, 17, 41, 13, 41, there is a 70% chance of detection in 2.0 years and a 90% chance of detection in 3.1 years.

For comparison purposes, the sampling requirements for a univariate test of each parameter are also listed in Table 11. With the exception of volume, the discriminant combination produced a smaller sample requirement than any of the cell parameters individually. The volume parameter only produced a smaller sample requirement at the .50 and .70 power levels. For power levels of .90 and .95, volume has greater sampling requirements than the discriminant function.

It is interesting to note that the relative importance of the volume and area parameters are reversed in Tables B-9 and 11. In Table B-9, the results indicate that it is easier to detect a given percent increase in area than in volume. In Table B-ll, the results indicate that when the increase is adjusted to allow for the likelihood of obtaining such an increase, the volume parameter is easier to detect than the area parameter.

The advantages one derives from the use of the discriminant function are clearly evident. The use of the multivariate discriminant test provides 1) a smaller detection time (with the exception of cell volume) than the corresponding univariate tests, and 2) a measure of the relative importance of each variable in discriminating between the experimental units (storms). It is also

Table B—11. A comparison of sampling requirements between individual parameters and the discriminant combination for the same percentage increases (Sampling Model #1, a=.05)

Parameter	Power	Sample size required for a C_e** standard error-increase 2.0	3.0	4.0	8.0
Discriminant Combination	.50	4.7	2.2	1.4	<1.0
	.70	6.8	3.3	2.0	<1.0
	.90	10.6	5.1	3.1	1.0
	.95	12.7	6.1	3.7	1.2
Volume	.50	3.8(28)*	1.8(43)	1.1(59)	<1.0(132)
	.70	6.6	3.1	1.8	<1.0
	.90	12.0	5.7	3.4	1.0
	.95	15.1	7.2	4.3	1.3
Mean Rain	.50	5.5(17)	2.6(25)	1.6(34)	<1.0(67)
	.70	9.6	4.6	2.7	<1.0
	.90	17.4	8.3	5.0	1.6
	.95	22.0	10.5	6.3	2.0
Area	.50	5.0(10)	2.3(14)	1.4(19)	<1.0(38)
	.70	8.7	4.0	2.4	<1.0
	.90	15.9	7.4	4.3	1.3
	.95	20.0	9.3	5.5	1.6
Duration	.50	9.1(9)	4.2(13)	2.5(17)	<1.0(35)
	.70	15.8	7.3	4.3	1.2
	.90	28.9	13.4	7.8	2.2
	.95	36.5	16.9	9.9	2.8
Maximum Rain	.50	5.9(20)	2.8(31)	1.7(41)	<1.0(82)
	.70	10.2	4.9	3.0	1.0
	.90	18.6	9.0	5.5	1.8
	.95	23.5	11.4	6.9	2.3
Maximum Area	.50	5.5(7)	2.5(10)	1.5(13)	<1.0(27)
	.70	9.5	4.4	2.5	<1.0
	.90	17.4	8.0	4.6	1.3
	.95	21.9	10.0	5.8	1.6
Minimum Rain	.50	4.7(21)	2.3(31)	1.4(41)	<1.0(82)
	.70	8.2	4.0	2.4	<1.0
	.90	14.9	7.2	4.4	1.4
	.95	18.8	9.1	5.6	1.8

*Number in parenthesis is the percentage increase of a parameter from its mean value.

**C_e is the number of standard errors, possible that the detection times could be decreased by including the cell information obtained from the radar and the cloud physics aircraft; certainly this possibility should be explored using the data collected during the 1975 and 1976 field operations.

Increases based on the standard errors were also imposed on the data contained in Sampling Model #2, and the results are listed in Table B-12. The discriminant combination requires less detection time than any of the individual parameters with the exception of volume at the .50 power level. A comparison of Tables B—11 and 12 reveals that for a given number of standard errors, the detection times are shorter for Sampling Model #2 than for Sampling Model #1. This is a noteworthy result because: 1) Sampling Model #2 does not contain any imbedded cells (at initiation time), and 2) an attempt has been made to minimize the contamination problem. This indicates that one should be able to conduct a successful single cloud experiment by dealing only with those clouds that are initially isolated from the rain system. However, it is noted that for approximately the same hypothesized increase (59% for Sampling Model #1 and 58% for Sampling Model #2), the imbedded case, Sampling Model #1, has somewhat smaller detection times than the isolated case.

One of the advantages derived from defining the storm to be the experimental unit is that one has the opportunity to delineate the experimental unit with respect to synoptic type. For Sampling Model #1, there were 60 cells in the air mass category, 120 cells in the squall line category, and 119 cells in the squall area category. It is of interest to determine what the sampling requirements would be if the seeding activities were limited to a particular synoptic type. Therefore, the log-normal model and increases based on standard errors were used in conjunction with the discriminant method to obtain sampling requirements for the squall line, squall area, and air mass storms. The results are listed in Table B-13 along with the results for all types from Table B—11.

In general, for squall line and squall area storms a longer detection time is necessary than for all types combined. For example, there is a 70% chance of detecting a 4 standard-error increase in 2.0 years for all synoptic types, whereas 3.3 and 2.8 years are needed for squall line and squall area classifications. However, the air mass storms require approximately the same detection times as all synoptic types. The percent increase combinations with these standard error increases are listed in Table B-14-For the 4.0 standard-error increase, the percent increases for the 'volume, mean rain, area, duration, maximum rain, maximum area, minimum rain' combination are 59, 34, 19, 17, 41, 13, 41 for all synoptic types, 113, 57, 36, 30, 69, 25, 66 for squall lines, 111, 53, 38, 33, 60, 26, 63 for squall areas, and 113, 63, 37, 48, 66, 32, 100 for air-mass rains.

Tables B-13 and B-14 can be used to obtain estimates of the sampling time lost when one seeds only a particular synoptic type. Thus, these tables afford the opportunity to weigh this loss against the additional physical information that might be derived by tailoring the treatment to a particular rain structure (i.e., synoptic type).

It has been demonstrated elsewhere in this report that an average measurement error of at least 10% is to be expected with any raingage network or

Table B-12. A comparison of sampling requirements between individual parameters and the discriminant combination for the same percentage increases (Sampling Model #2, α=.05)

		Sample size required for a C standard error-increase of:			
Parameter	Power	2.0	3.0	4.0	8.0
Discriminant Combination	.50	2.7	1.4	<1.0	<1.0
	.70	3.9	2.0	1.3	<1.0
	.90	6.1	3.0	1.9	<1.0
	.95	7.2	3.6	2.3	1.0
Volume	.50	2.8(38)*	1.3(58)	1.0(80)	<1.0(182)
	.70	4.8	2.3	1.4	<1.0
	.90	8.8	4.2	2.6	<1.0
	.95	11.1	5.3	3.2	1.0
Mean Rain	.50	3.6(23)	1.8(35)	1.1(46)	<1.0(93)
	.70	6.2	3.0	1.9	<1.0
	.90	11.3	5.5	3.4	1.1
	.95	14.3	7.0	4.3	1.4
Area	.50	4.4(12)	2.1(17)	1.2(23)	<1.0(47)
	.70	7.6	3.6	2.1	<1.0
	.90	13.9	6.5	3.9	1.2
	.95	17.6	8.2	4.9	1.5
Duration	.50	9.9(10)	4.6(15)	2.7(20)	<1.0(40)
	.70	17.2	8.0	4.7	1.4
	.90	31.4	14.6	8.6	2.5
	.95	39.6	18.4	10.8	3.2
Maximum Rain	.50	3.5(30)	1.7(45)	1.0(61)	<1.0(121)
	.70	6.0	3.0	1.9	<1.0
	.90	11.0	5.5	3.4	1.2
	.95	13.9	6.9	4.3	1.5
Maximum Area	.50	4.9(8)	2.3(12)	1.3(16)	<1.0(32)
	.70	8.5	3.9	2.3	<1.0
	.90	15.5	7.2	4.2	1.2
	.95	19.6	9.0	5.3	1.5
Minimum Rain	.50	2.0(26)	1.0(39)	<1.0(52)	<1.0(103)
	.70	3.4	1.7	1.0	<1.0
	.90	6.3	3.1	1.9	<1.0
	.95	8.0	3.9	2.4	<1.0

"Number in parenthesis is the percentage increase of a parameter from its mean value.

Table B-13- A comparison of the sampling requirements of squall lines, squall areas, air mass, and all types for the discriminant approach (α=.05, Sampling Model #1)

Type	Power	Sample size required for a C_e standard error increase of: 2.0	3.0	4.0	8.0
All Types	.50	4.7	2.2	1.4	<1.0
	.70	6.8	3.3	2.0	<1.0
	.90	10.6	5.1	3.1	1.0
	.95	12.7	6.1	3.7	1.2
Squall Line	.50	7.1	3.6	2.3	<1.0
	.70	10.5	5.2	3.3	1.3
	.90	16.2	8.1	5.1	1.9
	.95	19.3	9.6	6.0	2.2
Squall Area	.50	6.1	3.1	2.0	<1.0
	.70	8.9	4.5	2.8	1.1
	.90	13.7	6.9	4.3	1.6
	.95	16.4	8.2	5.1	2.0
Air Mass	.50	4.1	2.3	1.6	<1.0
	.70	5.9	3.3	2.3	1.2
	.90	9.0	5.0	3.4	1.7
	.95	10.7	5.9	4.0	2.0

combination of radar and raingages that is likely to be used in the single cloud experiment. Consequently, the effect of measurement errors should be given consideration when computing sampling requirements. This is done by assuming that the standard error of the mean is 10%, 20%, and 30% greater than the standard error used for the calculations of the previous tables. Equation B-10 is then used to obtain the revised percentage increases. The resulting percentage increases for the 2.0, 3.0, 4.0 and 8.0 standard errors are listed in Table B-15-

The interpretation of Table B-15 requires a comparison with Table B—11. For example, it required 2.0 years to detect a 4 standard error increase with a 70% chance of detection (Table B—11). The associated percent increase combination is 59 (volume), 34 (mean rain), 19 (area), 17 (duration), 41 (maximum rain), 13 (maximum area), 41 (minimum rain). If there is a measurement error of 10%, it requires a combination of increases of 66, 37, 21, 19, 45, 15, 45 as compared to the combination associated with the 4 standard error increase with no measurement error given above. If a 30% measurement error is present, the combination of percent increases is 80, 44, 25, 22, 53, 17, 53.

Table B-14. Percentage increases associated with the sampling requirements of synoptic types for the discriminant approach in Table 13.

Parameter	Percentage increases for a C standard error-increase of: 2.0	3.0	4.0	8.0
	All Types			
Volume	28	43	59	132
Mean Rain	17	25	34	67
Area	10	14	19	38
Duration	9	13	17	35
Maximum Rain	20	31	41	82
Maximum Area	7	10	13	27
Minimum Rain	21	31	41	82
	Squall Line			
Volume	52	81	113	267
Mean Rain	29	43	57	114
Area	18	27	36	71
Duration	15	23	30	60
Maximum Rain	35	52	69	138
Maximum Area	13	19	25	50
Minimum Rain	33	50	66	182
	Squall Area			
Volume	50	79	111	262
Mean Rain	26	40	53	106
Area	19	28	38	76
Duration	17	25	33	66
Maximum Rain	30	45	60	120
Maximum Area	13	20	26	52
Minimum Rain	32	47	63	127
	Air Mass			
Volume	56	88	113	293
Mean Rain	31	47	63	126
Area	18	28	37	74
Duration	24	36	48	97
Maximum Rain	33	50	66	133
Maximum Area	16	24	32	64
Minimum Rain	50	75	100	201

Table B–15. Percentage increases associated with the sampling requirements of Sampling Model #1 when the standard error is altered by measurement error

	Assumed measurement error of:			
Parameter	0%	10%	20%	30%
2 standard error-increase				
Volume	28	31	34	37
Mean Rain	17	19	20	22
Area	10	11	12	13
Duration	9	9	10	11
Maximum Rain	20	23	25	27
Maximum Area	7	7	8	9
Minimum Rain	21	23	25	27
3 standard error-increase				
Volume	43	48	53	58
Mean Rain	25	28	30	33
Area	14	16	17	19
Duration	13	14	16	17
Maximum Rain	31	34	37	40
Maximum Area	10	11	12	13
Minimum Rain	31	34	37	40
4 standard error-increase				
Volume	59	66	73	80
Mean Rain	34	37	40	44
Area	19	21	23	25
Duration	17	19	21	22
Maximum Rain	41	45	49	53
Maximum Area	13	15	16	17
Minimum Rain	41	45	49	53
8 standard error-increase				
Volume	132	148	165	182
Mean Rain	67	74	81	88
Area	38	42	46	50
Duration	35	38	41	45
Maximum Rain	82	90	98	107
Maximum Area	27	29	32	35
Minimum Rain	82	90	99	107

b. Other randomizations

The sampling requirements presented in the various tables pertain to a 50-50 randomization scheme. If it is desired to test more than one seeding technique (e.g., cloud base seeding and cloud top seeding), or more than one basic hypothesis (e.g., dynamic seeding and "precipitation screening") the sampling time increases. "No treatment" is also considered to be a treatment in the context of experimental design, so the addition of one more treatment results in a three-way randomization (33-33-33) instead of the 50-50. The additional treatment can be incorporated into the Single Cloud design (also, for our purposes, a random-experimental design) in the following manner.

Even though the randomization is 33-33-33, there is an equal number of experimental units in each treatment (assuming proper balancing), and each seeded treatment is related to the non-seeded treatment through a 50-50 randomization. Thus, if N^1 (50-50 randomization) has been determined by Equation 1 or by the discriminant approach, it will require N'/2 additional observations in order for each treatment to have a 50-50 randomization with the non-seeded sample. This ensures a 33-33-33 randomization when all three treatments are considered. If we let the total number of treatments, non-seeded treatment included, be equal to k, then, in general, the number of observations required (N.) is given by:

$$N_k = N^1 \ k/2 \tag{11}$$

Consequently, if there are 3 treatments (33-33-33 randomization), then k=3, and all the previous tables relating to the sampling requirements for a 50-50 randomization scheme would need to be multiplied by 3/2 to obtain the proper detection times. In the same manner, for a four-way randomization scheme (25-25-25-25), the tables would need to be multiplied by 4/2. Clearly, then, the tables can be used to obtain sampling requirements for various randomization schemes.

c. Reduction of detection times

It would seem that the detection times might be reduced somewhat if cells not monitored by aircraft were also used in the evaluation. However, it is noted that the efficiency in a 2-sample test is the greatest when the sample sizes of the seeded and non-seeded groups are nearly the same (Neyman and Scott, 1967; Schickedanz and Changnon, 1970). A greater possibility of reducing the detection times would occur if one allowed the selection of cells to occur anywhere in the radar circle of coverage (provided that the 5-cm radar is adequate for evaluation of rainfall). However, it is unlikely that one pair of seeding and cloud physics aircraft will be able to effectively treat and monitor more than 2-3 cloud complexes per storm. For the aircraft sampling schemes assumed in this report with regard to the METROMEX data, the average number of cells selected for one sampling scheme was about 3.0 and was only 2.0 for the other. Smith, et al., (1974) suggest that their experience in Texas indicates that on the average, 3-6 cloud complexes can be treated per day. Thus, it is doubtful that the number of clouds sampled can be materially increased when the entire radar circle of coverage is used unless additional resources are available. However, the use of the entire radar circle will provide a greater probability of ensuring that an adequate number of storms (experimental units) will be obtained.

d. Network size

If the 5-cm radar system is inadequate for measuring rainfall from the single cloud, and if the rain evaluation must be based on a dense network of raingages, the network will need to be enlarged from the 1554 km^2 (600 mi^2) network which will be used for HIPLEX operations during the summer of 1976. This is obvious when one considers that the climatology of cell sampling reveals that the number of raincells detected on a 1295 km^2 network is only 22.7% of the number detected on a 5180 km^2 network.

V. Other Considerations

Regardless of the randomization scheme, the measurement error present in the data, or the cell and storm sampling aspects, predictor variables (covariates) can be included in the design to increase the sensitivity of the test. These predictor variables can be observed or calculated, a large- or cloud-scale parameter. For the Single Cloud experiment, the predictor variables can be used to screen out situations in which the modification hypothesis is applicable and for which positive treatment results are predicted (Calvin, et al., 1974). In the a real experiment, predictor variables can be used to decrease the experimental error and thereby increase the precision of the experiment. Examples of their potential use in reducing sampling requirements in the design of hail suppression experiments are given by Schickedanz and Changnon (1970), and Changnon and Morgan (1976).

Furthermore, if the day or the storm is used as the experimental unit in the Single Cloud experiment, one can combine the exploratory stage of the areal experiment with the Single Cloud experiment. Moreover, if meaningful predictor variables are available, they can be incorporated to strengthen the evaluation process. Research that involves daily and storm predictors is the subject of Appendix C.

Insofar as extra-area effects apply to the Single Cloud experiment, it would appear that the major effect might be re-distribution of rainfall. That is, the concept of the "survival of the fittest" may predominate such that when the first cumulus clouds begin to develop into rain-producing entities, they tend to "rob" the available energy from surrounding clouds. This could easily cause a re-distribution of rainfall to take place within the area. It is conceivable that there may be an equal probability within a region as to which cloud will develop first, and that this might determine the probability distribution for the chain of events during the remainder of the day. Certainly, during the 1976 summer operations, the analysis should be performed using the radar and rainfall data in an attempt to determine the influence of the initial convective cloud development on the other clouds in its vicinity.

In regard to the early stages of the Single Cloud experiment, the extra-area effort is primarily limited to the monitoring of local effects on surrounding clouds and convection within the storm. This will be accomplished primarily with radar data, satellite data and National Weather Service precipitation data. However, during the area experiment, an effort to establish downwind effects must be an integral part of the experiment. Such an effort is considered essential because of limited evidence supporting extra-area effects and the mechanisms proposed for their existence.

Elliott, et al. (1974) suggest that certain meteorological variables in the downwind area be measured and analyzed using 1) synoptic surface and upper air data and analysis, 2) radar data, 3) aircraft data, 4) satellite data, and 5) precipitation samples (for silver content analysis). The synoptic surface and upper air data are being addressed by the kinds of analyses described in Appendix C. This work is being continued and should provide excellent information in regard to the utility of surface and upper air analyses in relation to the downwind problem.

Elliott, et al. (1974) suggest that the radar should be used to monitor lines of echoes, thereby providing valuable information on establishing and quantifying downwind effects of seeding. It is noted that these types of analyses support the choice of the storm as the experimental unit. Since the storms would be seeded at random, the monitoring of them by the radar, satellite, and aircraft along with the samples of silver in the downwind area, will provide some valuable input into the extra-area problem as the Single Cloud experiment is being conducted. We recommend that the collection of the observations suggested by Elliott et al. (1974) be included in the HIPLEX program. It is also recommended that the statistical methods suggested by Schickedanz (1974) be applied to daily and storm precipitation to aid in the evaluation. Furthermore, the use of EOF (Empirical Orthogonal Function) analyses (Schickedanz and Ackermann, 1976) is strongly recommended. A detailed description of measurement and analysis procedures for the extra-area problem will be forthcoiwng as the design for the areal experiment is developed.

VI. Summary and Discussion

In an experimental (as opposed to operational) program, one of the basic requirements placed on the design is that of randomization. The most commonly used design in recent years has been the random-experimental design, which involves the randomization of the experimental unit (usually days or sub-sets of days) over a single target area into seeded and non-seeded units. The evaluation is usually based on the daily rainfall or hailfall averaged over the target area. The cloud physicists have often criticized this design, claiming that the statisticians are "running the show" and are not properly accounting for the physical considerations in their evaluation process. However, Simpson and Woodley (1974) departed from this trend and produced some excellent results through the use of model considerations dealing with the single cloud element. A single cloud design allows for the testing of physical parameters more readily than other comtemplated designs. It was this that led DAWRM to select the single cloud as the most promising design to use in HIPLEX at this time.

However, the single cloud design also places severe constraints on the measurement system since the tracking of single clouds in time and space to a sufficient degree of accuracy requires 1) a dense network of surface raingages, 2) a very accurate and sophisticated 10-cm radar system, or 3) a combination of the dense network and radar system. Whether or not the 5-cm radar system or even a 5-cm radar-raingage mix can adequately measure the precipitation awaits the results of the HIPLEX field program during the summer of 1976. Assuming that the measurement system will be adequate for individual clouds, we recommend that the treatment and randomization be applied to the storm, a group of clouds. Since the experimental unit is defined to be the unit to which the treatment is applied, the choice of randomization also determines the experimental unit. However, we recommend that the effect of the treatment be measured on the sampling unit, which can be some fraction of the experimental unit and, in this case, is to be the single cloud. Thus, it is recommended that the *experimental unit for the single aloud experiment should be the storm and the sampling unit should be the individual cloud (cell).*

The single cloud is rejected as the experimental unit because of 1) interaction and, hence, contamination between clouds in multicellular convective systems, 2) difficulties in cell recognition prior to treatment and hence the danger of sacrificing *a priori* statistical inference for *a posteriori* inference, and 3) danger that the definition of the experimental unit may be jeopardized by the merger of individual clouds or cells. It would appear that the choice of the cloud (or raincell) to be the sampling unit instead of the experimental unit permits a variety of definitions without severely affecting the statistical inferences, and it also provides greater flexibility in testing physical hypotheses.

Although we firmly believe that the single cloud (cell) should not be used as the experimental unit, it is recognized that the choice between the storm or the day as the experimental unit is not so easily determined. It would appear, however, that the opportunity to meaningfully determine the synoptic type for each experimental unit would be a decided advantage; such a determination is not always possible if the day is used as the experimental unit.

Since the dominating force in determining the character of the rainfall within a storm is the synoptic weather situation, the ability to make this distinction removes an extraneous source of variation which, in turn, increases the precision of the experiment. It is recognized that there may be a contamination problem from storm to storm, but the contamination problem can be handled by either allowing a buffer period or buffer area to occur in which no seeding takes place or by skillfully stratifying the storm during the analysis stage into categories of potentially contaminated storms and into storms where there is little chance that contamination occurred. The choice of the storm as the experimental unit also provides an opportunity to assess downwind effects if proper measurements (i.e., synoptic surface and upper air, radar, satellite, aircraft and silver detection) are available to permit the tracking of the seeded and non-seeded storms into the downwind area. *It is noted, however, that the use of the storm as the experimental unit requires a method of real time storm recognition and delineation, based on radar or aircraft, that must be developed during the HIPLEX operations during the summer of 1976. This is absolutely essential; if such a method is not available, the experimental' unit will have to be based on the day instead of the storm.*

In this scheme, the randomization would be conducted in the following manner: the storm (experimental unit) is delineated as it approaches the network or as it initiates on the network. The storm would be identified in real time by airborne scientists in radio communication with the radar. The entity must be clearly recognizable to both the airborne scientist by eyeball and the radar scientist, as an isolated echo or close group of echoes. If the storm is designated to be a seeded storm, all cells selected by the cloud aircraft and/or radar controller during the storm are to be seeded. The cloud physics aircraft monitors the cells by collecting the physical measurements of interest. If the storm is designated to be a non-seeded storm, cells are selected in the same manner as if they were to be seeded, and the cloud physics aircraft monitors the storm system as before. (This is necessary in order to provide a valid control sample for the experimental design.) It is possible that another seeding aircraft could be used to handle other incoming storms. This would provide another set of data that, although cloud physics measurements would be unavailable, would provide a wealth of data for evaluation based on the radar and dense raingage information. A final point concerning randomization is that the concepts of grouping, blocking, and balancing should certainly be employed.

In regard to evaluation, it is strongly recommended that one should employ multivariate statistical tests instead of univariate tests. In particular, the use of discriminant analysis provides 0 a method of including characteristics not only from the radar (echo base ht., echo tops, area of cloud base, etc.) but also from the cloud physics measurements and the rainfall characteristics from individual cells at the surface, 2) a measure of which cell characteristic is the most important parameter with regard to distinguishing potential differences between seeded and non-seeded cell characteristics, and 3) a reduction of the detection times since more information concerning the radar, physics, and surface rainfall can be included.

Since a climatological data base of surface raincells and radar cells determined by the 5-cm radar system was not available, METROMEX rain data from the period 1971-1973 were used to obtain approximations of detection times required. For a discriminant combination of increases in volume of 43%, mean rain of 25%, area of 14%, duration of 13%, maximum rain of 31%, maximum area of 10%, and minimum rain of 31%, there is a 70% chance of detection in 3.3 years. In order to have a 90% chance of detection, 5.1 years would be required. For the same discriminant combination as above, but with percentage increases of 59, 34, 19, 17, 41, 13, 41, respectively, there is a 70% chance of detection in 2.0 years and a 90% chance of detection in 3.1 years. The first discriminant combination was based on a 3 standard error-increase and the second on a 4 standard error-increase (see section 4a) of this appendix.

Predictor variables (covariates) should be included in the design to increase the sensitivity of the test. These predictor variables can be of synoptic, meso-, or cloud scale. These variables can be used for screening and stratification as well as for reducing the sampling requirements. If the storm is used as the experimental unit, there is opportunity for a meaningful combination of the single cloud experiment, the exploratory stage of the areal experiment, and the utilization of predictor variables.

Such a combination would materially sharpen the evaluation process, and research involving areal and storm predictors is underway (Appendix C). Only preliminary results are available at this time, but more detailed and complete results will be forthcoming in the months to come.

Finally, it is essential that the types of statistical analyses described in this appendix be repeated using the radar, cloud, and surface "cells" which will be monitored during the summer of 1976 in order to firm up the estimates obtained from the METROMEX rain data.

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APPENDIX C

ENVIRONMENTAL PREDICTOR VARIABLES FOR HIPLEX

I. Introduction

Predictor variables for HIPLEX are parameters which can provide some estimate of the growth and precipitation potential of convective clouds. The term "predictors" is used throughout this document in a very general way to include covariates, estimators, stratification parameters, as well as predictors for forecasting purposes. They play a critical role in HIPLEX by providing homogeneity in sample populations, thereby decreasing the variance and increasing the sensitivity of the statistical tests. The use of environmental predictors is important for both the single cloud and area experiments. Ongoing research to identify environmental predictors of areal and storm rainfall is the subject of this appendix. Only preliminary results are available at this time, but more complete results will be forthcoming in the months to follow.

II. Literature Review-Survey of Potential Predictors of Convective Rain

The predictor variable development for the High Plains Experiment (HIPLEX), is based in part on an extensive literature review directed toward the identification and evaluation of synoptic variables that are correlated with convective rainfall. Many predictor variables have been identified for other parts of the country and/or for other convective phenomena (hailstorms, tornado producing thunderstorms). However, all of these should, and are, being assessed for applicability in HIPLEX. Some that are correlated with convective precipitation in another part of the country may have little or no correlation with High Plains convective precipitation. The converse is also possible.

About 200 "candidate" predictor variables have been found thus far. Many of these can be determined at several levels in the atmosphere so that potentially the number may increase to much beyond 200. Other possible predictor variables could be synthesized but it is doubtful they would improve upon these already identified. Most of the candidates have been screened out as poorly correlated with convective phenomena; however, all predictor variables are reviewed in this section in order to avoid duplication of effort by others.

All of the predictor and estimator variables address at least one of three physical states important for the development of convective rainfall-producing systems. These are the stability, the availability of moisture, and the triggering mechanism. Variables related to stability range in complexity from a measure of the thickness between two levels and the vertical totals index (Miller, 1967) to indices that measure the positive area between the temperature curve for a parcel lifted from the surface layers to 500 mb and the environmental temperature curve for the same layer (Williams, 1968). Moisture predictor variables are generally simple measures of the vapor content , dewpoint, relative humidity, specific humidity, etc. for either a point or a layer. More complicated measures of the state of the moisture field, such as gradients and advection, can be derived from spatial analyses.

Predictor variables indicative of triggering mechanisms address a wide range of surface and upper air phenomena. Quantities derived from field analyses such as upslope flow, convergence, vorticity, and the Laplacian of pressure or height, help identify areas where air masses undergo vertical displacements. Other predictor variables indicative of systems producing vertical motion include frontal positions, 500-mb height, 500-mb height gradients, vorticity advection, positions of low- and mid-level jet streams, and net vertical displacements of selected air parcels estimated from numerical trajectory-prediction models. Various combinations of these and others with parameters from the stability and moisture categories increase the number and complexity of predictor variables.

Listed in Table C-1 are authors and publication dates of papers which dealt with this problem (complete citations are given in the list of references). When predictor variables were correlated with convective phenomena other than rainfall, the phenomenon is also listed.

The predictor variables were found to fall within one of four categories:

1. Point predictor variables that are available from single soundings or single surface observations.

2. Line predictor variables that require two soundings or two surface observations in either a spatial or temporal setting.

3. Field predictor variables based on observed spatial distributions of meteorological parameters. (Various derivative quantities fall into this category.)

4. Field predictor variables derived from the output from numerical weather prediction models. These comprise an almost limitless number of possibilities and have the advantage that the predicted variable can be valid at the time operations are conducted and yet not be contaminated by side effects. The disadvantage of these predictors is that they contain the inaccuracies and poor resolution (particularly along the vertical coordinate) typical of today's numerical forecast models.

The candidate predictor variables are listed by category in Tables C 2-5. (The numbers in parentheses in these tables refer to the references listed in Table C-l). Some variables are ambiguous (no. 45 in Table 2, for example) and some are nearly redundant. These are given in order to provide a complete list of quantities which have in the past been investigated.

Most of the field predictor variables were derived for tornado conditions (Endlich and Mancusso, 1967; Charba, 1975). However, this does not lessen their potential importance to the general convective rain study, and in particular the heavier rains. Environmental conditions favorable for thunderstorms tend to maximize just prior to and during severe weather outbreaks.

Table C-1 References included in the predictor variable review

Reference

1. Achtemeier and Morgan (1975)
2. Bermowitz (1970
3. Bonner, Reap, Kemper (1970 (Tornado)
4. Boyden (1963)
5. Cahir (1970
6. Charba (1975) (Tornado)
7. Clark (1973)
8. Darkow (1968)
9. David (1974) (Tornado)
10. David and Smith (1970
11. Dennis, Koscielski (1969)
12. Dennis, Schock, Koscielski, Mielke (1967)
13. Dirks (1969)
14. Endlich and Mancusso (1967) (Tornado)
15. Estoque and Partages (1974)
16. Foster (1964) (Tornado)
17. Fujita and Bradbury (1966)
18. Galway (1956)
19. George (1960)
20. Glahn, Lowry, Hollenbaugh (1969)
21. Hammond and Clark (1975) (Tornado)
22. Harley (1970
23. Jefferson (1963)

2k. Maddox (1973) (Tornado)

25. Madigan (1959)
26. Miller (1967) (Tornado)
27. Miller, Bidner, Maddox (1970 (tornado)
28. Miller, Dennis, Boyd, Smith, Cain (1974)
29. Rackliff (1962)
30. Reap (1976)
31. Reap and Foster (1975)
    also Reap (1975)
32. Reap and Alaka (1969) (Tornado)
33. Renne and Sinclair (1969) (Hailstorm)
34. Schaefer (1975)
35. Schleusener and Auer (1964)
36. Showalter (1953)
37. Sly (1966)
38. Whitehead (1971) (Tornado)
39. Williams (1968)

Table C-2 List of point predictor variables that can be taken from single soundings or single surface observations.

(Numbers in parentheses are the references given in Table C-1)

1. Temperature (6, 9» 33)
2. Dewpoint temperature (9, 33)
3. Sea level pressure (6, 9)
4. Wind speed (9, 33)
5. Wind direction (9)
6. Cloudiness (9)
7. Visibility (9)
8. Cloud base height (9)
9. Moisture at 850 mb (13)
10. 500 mb dryness (13)
11. 700-900 mb relative humidity (RH) or humidity in general (13)
12. RH 1000-600 mb (15)
13. Dew point at Goodland, Kansas 06Z (35)
14. Dew Point at Cheyenne, Wyoming 06Z (35)
15. 500 mb temp over Denver, Colorado (DEN) 00Z (35)
16. 500 mb height over DEN 00Z (35)
17. Surface mixing ratio (6)
18. Surface wet bulb potential temperature (6, 39)
19. Surface isobaric equivalent potential temperature (6)
20. Maximum mean wet bulb potential temperature (6w) for a 100 mb column within a 160 mb column (39)
21. Maximum mean 0w for a 160 mb column within a 240 mb column (39)
22. Station pressure (39)
23. Previous day's maximum temperature in Colorado (35)
24. Previous day's maximum temperature in Wyoming (35)
25. Previous day's maximum precipitation in Wyoming (35)
26. Previous day's maximum precipitation in Kansas (35)
27. Previous day's $\log_{10} E_{max}$ (maximum hail impact energy ft-lb/ft^2) in Colorado or Nebraska (35)
28. Precipitable water >.75 inches (28)
29. Precipitable water to 500 mb > .70 (11)
30. 1000-850 mb thickness (39)
31. 1000-500 mb thickness (39)
32. Saturation thickness (20)
33. 700-500 mb saturation thickness defined as the 700-500 mb thickness minus the thickness of the 700-500 mb layer given the temperatures along the ascent of a 160 mb deep air column that originates near the surface (39)
34. Severe storm positive area. The saturation thickness from the level of free convection to 500 mb (see 33) using a 100 mb deep moist column (39)
35. Pressure at the lifted condensation level (LCL) (39)
36. Pressure at the level of free convection (LFC) (39)
37. Pressure at the base of the 100 mb moist layer (see 20) (39)
38. Pressure at the convective condensation level (CCL) (39)
39. Convective temperature (39)
40. Height of the CCL (25, 33)

Table C-2 cont.

41. Height of the LCL (25)
42. Height of the freezing level (25)
43. Height of the wet bulb zero (25)
44. Depths of layers where the mixing ratio was greater than 3,5,8 g/kg (25)
45. Stability indices (no detail) (13, 25)
46. Showalter index (12, 15, 33, 36, 39)
47. Lifted index (12, 18, 33, 38)
48. K-Index (19, 39)
49. Total energy index (8, 33)
50. Convective index positive area. The same as severe storm positive area (34) except using a 160 mb deep moist column. (39)
51. Severe storm index. The severe storm positive area plus the negative area between the LCL and LFC (39)
52. Convective index. The same as severe storm index except use a 160 mb deep moist column (39)
53. Summer index (5)
54. Vertical Totals index (temperature at 500 mb minus temperature at 850 mb) (26)
55. Cross Totals index (500 mb temperature minus 850 mb dew point temperature) (26)
56. Total Totals index (sum of the Vertical Totals with the Cross Totals) (26)
57. Sly index (37)
58. Best lifted index (17)
59. Potential wet bulb index (10)
60. Surface potential index (24)
61. Boyden index (4)
62. Rackliff index (29)
63. Latent and potential instability index (22)
64. 500 mb temperature minus the temperature at 500 mb of the wet bulb curve passing through the sea level wet bulb temperature (16)
65. Jefferson index (23)
66. SWEAT index (27, 38)
67. Low level jet on 12Z sounding (13)
68. Direction of averaged prevailing winds 1000-600 mb (15)
69. 850 mb wind speed > 15 kt (11, 28)
70. 850 mb wind direction 270-120 clockwise (11, 28)
71. 500 mb wind speed (33)
72. Positive vertical wind shear (13)
73. 850-200 mb vertical wind shear (15)
74. Sine day of year (30, 31)
75. Cosine day of year (30, 31)
76. Sine latitude (30, 3D
77. Cosine latitude (30, 3D
78. Solar altitude (30, 3D

Table C-3 List of line predictor variables that require two soundings or two surface observations in either a spatial or temporal setting for their calculation.

(Numbers in parentheses are the references given in Table C-1)

1. *2k* hr change in difference of reduced sea level pressure between Cheyenne, Wyoming and Trinidad, Colorado, 06Z (35)
2. *2k* hr change in difference of reduced sea level pressure between Kansas City, Missouri and Amarillo, Texas, 06Z (35)
3. *2k* hr change in dew point at Goodland, Kansas 06Z (35)

k. *2k* hr change in dew point at Oklahoma City, Oklahoma, 06Z (35)

5. *2k* hr change in dew point at Cheyenne, Wyoming, 06Z (35)
6. *2k* hr change in 500 mb temp over Denver, Colorado 00Z (35)
7. *2k* hr change in 500 mb height over Denver, Colorado, 00Z (35)
8. *2k* hr change in maximum temp observed the previous day in Wyoming (35)
9. Difference in reduced sea level pressure between Cheyenne, Wyoming and Trinidad, Colorado (35)
10. Difference in reduced sea level pressure between Kansas City, Missouri and Amarillo, Texas (35)
11. Surface temperature tendency(6)
12. Tendency of the mean sea level pressure (6)
13. Surface mixing ratio tendency (6)
14. Surface wet bulb potential temperature tendency (6)
15. Isobaric equivalent potential temperature tendency (6)
16. Spokane and Tatoosh, Washington 700 mb temperature (35)
17. Dodge City, Kansas minus North Platte, Nebraska, 700 mb height (35)

These same conditions are present in general thunderstorm outbreaks but are perhaps less intense and not in the same order of importance as in severe thunderstorm outbreaks.

The results of the various studies in the literature varied, depending on the geographical location and the predictand. All of the studies that included moisture found that rainfall was critically dependent upon an abundant moisture supply. Convective rainfall over Florida was inversely correlated with stability (Estoque and Partagas, 1974) but convective rainfall over the central and northern High Plains showed little or no correlation with stability (Madigan, 1959; Dennis et al., 1967). The precipitation regime in Florida differs from the precipitation regime in the High Plains. A goodly fraction of summer precipitation in Florida is due to air mass shower activity which results when solar insolation heats the surface layers and releases latent convective instability. A convectively unstable environment above 850 mb often extends over large areas of the Florida Peninsula and the southeastern U. S. and tends to persist from the early morning time of the sounding throughout the day. Thus, the early morning sounding yields information pertaining to the midafternoon stability.

The High Plains is characterized by three diverse precipitation regimes. These are the air mass shower type, the frequent system type (frontal, squall line, mesosystem) , and the mountain drift type. A possible explanation for the poor correlation between stability and precipitation draws upon the transience of the system type. Rapid destabilization can occur within mesoscale upward vertical velocity zones along and ahead of cold fronts and squall lines. Low level inversions have been destroyed over a period of time from 1-3 hours in advance of squall lines (Long, 1963). The temperature and moisture lapse rates within these convergent zones can be expected to differ considerably from the lapse rates obtained from the morning soundings unless these are located within the convergent zones. Thus, the stability predictor variables derived from morning soundings are likely to have little or no correlation with events that occur later in the day.

The mountain drift type precipitation events may also have little or no correlation with stability indices. Afternoon thunderstorms form over the mountains and tend to drift eastward over the High Plains as they dissipate. These clouds originate within local mountain induced circulations and are transient systems that have little or no dependence upon the low level stability over the plains.

A number of excellent predictor variables that address the triggering mechanisms have been developed. Mid-level vorticity advection (Dennis et al., 1967; Dennis and Koscielski, 1969), surface convergence (Bermowitz, 1971; Charba, 1975; Endlich and Mancusso, 1967; Renne and Sinclair, 1969; Reap and Alaka, 1969; Reap and Foster, 1975; Reap, 1976), boundary layer vertical velocity (Achtemeier and Morgan, 1975; Whitehead, 1971; Reap, 1975; Bonner, Reap and Kemper, 1971) and vertical displacements of air trajectories (Bonner, Reap and Kemper, 1971; Hammond and Clark, 1975; Clark, 1973; Reap and Foster, 1975; Reap, 1976; Reap and Alaka, 1969) have been found to be highly correlated with convective precipitation and severe weather occurrences. A less sophisticated predictor variable based upon the location of nearby fronts (Dirks, 1969) was not well correlated with convective precipitation.

Table C-4 List of field predictor variables (not predicted) that rely upon spatial distributions of variables.

(Numbers in parentheses are the references given in Table C-1)

1. Upper level trough (13)
2. Strength 500 mb flow (13)
3. Curvature 500 mb flow (13)
4. 700 mb dew point gradient (14)
5. 500 mb cold advection (13)
6. Temperature gradient near tropopause (14)
7. Maximum 500 mb wind over Utah or Colorado 00Z (35)
8. Maximum 500 mb wind over Arizona or New Mexico 00Z (35)
9. Wind speed at 200 mb (14)
10. Positive vorticity advection at 500 mb (11)
11. Position of surface fronts (13)
12. 24 hr change in maximum 500 mb wind over Arizona and New Mexico 00Z (35)
13. Temperature advection (sfc) (2)
14. Magnitude of the horizontal gradient of mixing ratio (6)
15. Product of the mixing ratio with the magnitude of its horizontal gradient (6)
16. Magnitude of the horizontal gradient of the wet bulb potential temperature, 6e, (6)
17. Product of 0e with the magnitude of its horizontal gradient (6)
18. Biconstituent diffusion (34)
19. Horizontal Laplacian of the MSL pressure (6)
20. The tendency of the horizontal Laplacian of the mean sea level pressure (6)
21. Pressure trough analysis (curvature of pressure field normal to trough axis) (1)
22. Divergence (sfc) (2, 6, 33)
23. Vorticity (sfc) (2, 6)
24. Surface moisture divergence (6, 14)
25. Surface moisture divergence tendency (6)
26. Equivalent potential temperature divergence (6)
27. Equivalent potential temperature divergence tendency (6)
28. Divergence of the temperature flux (14)
29. Horizontal divergence in the upper troposphere (14)
30. Frontogenesis of temperature (sfc) (2, 14)
31. Frontogenesis of moisture (14)
32. Terrain induced vertical velocity (6, 33)
33. Product of the equivalent potential temperature with the terrain induced vertical velocity (6)
34. The qw index (w is vertical velocity at top of 300 m layer) (38)
35. Cumulative lift (5 hr net surface layer vertical displacement) (1)
36. Thunderstorm forecast algorithm (cumulative lift is restricted to where the dew point temperature exceeds 50°F and to where the vector wind has a southerly component (1)
37. Vertical velocity at 850 mb (14)
38. Area between low level temperature and moisture axes (14)
39. Destabilizing temperature advection between low and mid-troposphere (14)
40. Destabilizing distribution of the divergence of the temperature flux between low and mid-troposphere (14)
41. Intersection of 850-500 mb 4260 thickness line and the thickness ridge (14)
42. Vorticity of the wind shear vector between 500 mb and the boundary layer (14)
43. Vortjcity acceleration (16)
44. Thunderstorm relative frequency distribution (30,31)

III. Predictor Variables for the High Plains

The candidate predictor variables culled from the literature (Tables C 2-5) have been reduced to a manageable number for study in the High Plains. The predictor variables derived from the output of numerical weather prediction models (Table C-5) have been dropped from consideration, at least for a first cut, because of the short lengths of the primitive equation (PE), limited fine mesh (LFM) and trajectory models archives. (The archives begin on 3 July 1969 (PE) , 1 October 1972 (LFM) and 3 July 1969 (Trajectory)).

In soliciting variables for study redundancy has to be eliminated and predictor variables that best address the physical processes that govern the meteorology of the High Plains chosen. The selected set should contain co-variates derived from as many of the fundamental meteorological variables (wind components, temperature, dewpoint temperature, pressure) as possible. Further, the set should contain co-variates that address the three physical categories: moisture, stability, and trigger mechanism.

The relatively poor correlation between rainfall and the stability indices for the High Plains (Madigan, 1959; Dennis et al., 1967) should not lead to the total elimination of stability-related predictor variables from the test set. Rather stability indices and other predictor variables that address thermodynamic structures should be extensively tested and poor candidates screened out.

Predictor variables that address triggering mechanisms should be sensitive to the presence of transient precipitation-producing systems. Therefore, high priority is placed upon co-variates that are derived from the hourly surface,observations.

Most of the predictor variables discussed on the pages to follow are taken directly from Tables C 2 through 5. Some have been modified slightly according to the meteorology and topography of the High Plains. For example, some stability indicies will be computed using the temperature and moisture at 900 mb instead of at the non-existent 1000 mb pressure level. Other predictor variables have been added, some on the recommendation of participants in the 1975 HIPLEX field program.

a. The Upper Air Predictor Variables

Table C-6 lists 27 estimator and predictor variables that can be computed from single soundings. These were selected for a pilot study for western Kansas for 13 Junes from 1958-1970. The predictor variables are to be correlated with the occurrence or non-occurrence of rain and with the rainfall depth. Those that correlate poorly will be screened out.

Dodge City, Kansas, is the radiosonde station used in the pilot study. The predictor variables were computed for the 1200 GMT (morning) soundings. It is possible that the predictor variables computed from the 0000 GMT (evening) soundings would be more highly correlated with precipitation, than those computed from the 1200 GMT soundings because late afternoon and, early evening is the climatolpgical time of maximum precipitation frequency for

Table C-5 List of predictor variables derived from the output from numerical weather prediction models.

(Numbers in parentheses are the references given in Table C-1)

1. Mean relative humidity from lowest 3 layers in 6 layer PE model (9)
2. Mean boundary layer potential temperature (9, 30)
3. Mean boundary layer sea level pressure (9)
4. Temperature (sfc, 850, 700, 500 mb 24 hour forecast (24F)) (3, 30, 31)
5. Dew point (sfc, 850, 700 mb 24F) (3, 30, 3D
6. Relative humidity (sfc, 850, 700 mb 24F) (3, 30, 3D
7. Mean relative humidity (sfc to 700 mb 24F) (30, 3D
8. Surface pressure (24F) (3, 30, 3D
9. Height of constant pressure surface (1000,850, 500 mb 24F) (3, 30, 3D
10. 1000-500 mb thickness (9)
11. Thickness (850 to 500 mb 24F) (30, 3D
12. Air parcel stability. The temperature difference between a parcel lifted from the surface to 500 mb and the forecast 500 mb temperature. (6)
13. Air parcel stability tendency (6)
14. Convective instability (sfc to 700 mb 24F) (defined as 700 mb Be) average 1000-850 mb θe (30, 3D
15. Horizontal temperature advection (850 mb 24F) (30, 3D
16. Dew point advection (700 mb 24F) (30, 31)
17. Temperature lapse rate (850 to 500 mb 24F) (30, 3D
18. Wet bulb potential temperature lapse rate (surface to 700 mb 24F) (30)
19. Height of wet bulb zero (24F) (30)
20. Convective instability (surface to 500 mb, 24F) (3, 32)
21. Magnitude of the horizontal dew point gradient (1000 mb 24F) (32)
22. Total Totals index (24F) (30, 3D
23. K-index (24F) (30, 3D
24. Showalter index (24F) (7, 30, 3D
25. Modified Showalter index plus 12 hour net vertical displacement at 700 mb (30)
26. SWEAT index (24F) (30)
27. Lifted parcel temperature advection at 500 mb (30)
28. 18-24 hour height change (30)
29. U component horizontal wind (boundary layer, 850, 700, 500 mb 24F) (3, 30, 3D
30. V component horizontal wind (boundary layer, 850, 700, 500 mb 24F) (3, 30, 31)
31. Wind direction (boundary layer, 500 mb 24F) (30, 3D
32. Wind speed (boundary layer, 500 mb 24F) (30, 3D
33. U wind component (500 mb) plus V component (boundary layer) (24F) (30)
34. U gradient (500 mb) plus V gradient (boundary layer 24F) (30)
35. Vector wind shear (24F) (30, 3D
36. U, V, components of mean boundary layer wind (9)
37. Moisture divergence (24F) (30, 3D
38. Wind divergence (boundary layer 24F) (30, 31, 32)
39. Relative vorticity (boundary layer 24F) (30, 3D
40. Geostrophic vorticity (1000, 500 mb 24F) (30, 3D

Table C-5 cont.

41. Thermal vorticity (1000 to 500 mb 24F) (30, 30
42. Vorticity advection (500 mb 24F) (30, 31)
43. 850 mb wind divergence (24F) (32)
44. 1000 mb temperature flux (24F) (32)
45. 1000 mb dew point flux (24F) (32)
46. Convergence (boundary layer, 850 mb 12F) (3)
47. 700 mb vertical velocity (9)
48. Vertical velocity (1000, 850, 650 mb 24F) (3, 30, 31)
49. Terrain induced vertical velocity (24F) (30, 31)
50. 12 hour net vertical displacement (sfc, 850, 700 mb) (3, 30, 31)
51. 24 hour net vertical displacement (sfc, 850, 700 mb) (3, 30, 31)
52. 48 hour vertical displacement from 500 mb (7)
53. Gradient of 12-hour net vertical displacement (30)
54. Trajectory convergence (sfc, 850 mb) (30, 31)
55. Convective instability times 12 hour 700 mb net vertical displacement (30, 31)
56. Modified Showalter index plus 12 hour net vertical displacement from 700 mb (30)
57. Convective instability times net vertical displacement of parcels ending at 500 mb during the last 6 hours of the forecast period (32)
58. Severe weather forecast trajectory and thermodynamics signature (21)
59. 6 hourly quantitative precipitation forecast (9)
60. Precipitation amount (24F) (3)

Table C-6. Predictor variables taken from soundings.

1. Layer precipitable water.
2. Total precipitable water.
3. Height of the convective condensation level.
4. Convective temperature.
5. Difference between the convective temperature and the 850 mb temperature.
6. Height where T = 0°C, T = -5°C, T = -10°C, T = -15°C, T = -20oc.
7. Warm convective depth - the difference between the height where T = 0°C and the height of the convective condensation level.
8. The mean mixing ratio between the surface and the convective condensation level.
9. K-index.
10. D-index.
11. Showalter index.
12. Lifted index.
13. Boyden index.
14. Cross Totals index.
15. Vertical Totals index.
16. Total Totals index.
17. Potential Wet Bulb index.
18. Energy index.
19. Severe Storm index.
20. Saturation deficit computed at the following levels:
    surface, 900, 850, 800, 700, 600, 500, 400, 200 mb.
21. Wind speed at the levels given in (20) except the surface.
22. Wind direction at the levels given in (20) except the surface.
23. Vector wind shear between 850 and 500 mb.

2k. Difference in wind direction between 300 and 700 mb.

25. The wind speed shear between 300 and 500 mb.
26. Temperature at mandatory levels.
27. Height at mandatory levels.

the High Plains, and much of this precipitation is initiated by spatially and temporally transient weather disturbances. However, the morning soundings were chosen because 1) the estimator and predictor variables can be useful objective aids for operational forecasts, and 2) there will be no possibility of modification of thermodynamic structures brought on by the seeding experiment.

Most of the estimator and predictor variables in Table 6 address stability (items 3, 4, 5, 9-19, 26, 27). A moisture category includes variables 1, 2, 8, 20. Variables 21-25 use the wind speed, wind direction, and variations of the wind with height to detect the presence and/or the approach of trigger mechanisms. Variables 6, 7 are aids for the refinement of the seeding effort. They give climatological information on the heights critical to seeding agent activation and on an estimate of depth of warm cloud through which the seeding agent must pass if released at cloud base. Note that the warm convective depth (variable 7) may differ from the actual warm depth of the cloud but short of using observed cloud bases (which are seldom available) there is no means of computing the latter.

The upper air predictor variables are calculated as shown below. The variable number refers to the list in Table 6.

Variables 1. and 2. The precipitable water (cm) for a layer is given by

$$P = \frac{\bar{q}}{g} (p_1 - p_2) \tag{1}$$

where $\bar{q}$ is the mean mixing ratio (gm/gm) for the layer, p is the pressure (dynes cm^{-2}) and g is the acceleration of gravity (103) cm sec^{-2}). The mixing ratio is calculated from the Clausis-Clapyron equation (Berry, *et al.*, 1945). The total precipitable water is the algebraic sum of the layer precipitable waters. We have chosen the individual layers to be bounded by the mandatory pressure levels given for the saturation deficit (item 20 in Table 6).

Variable 3. The height of the convective condensation level H_{CCL} (m) is given by the point of intersection of the sounding temperature curve with the saturation mixing ratio line that corresponds to the average mixing ratio in the "surface" layer below 820 mb. Following the development of Berry *et al.* (1945), page 703, we add 2 gm/kg to the layer average mixing ratio for the surface layer as defined above to approximate the increase in moisture expected from daytime evaporation from the ground. At each significant or standard pressure level, Tetan's equation is solved (Berry *et al.*, 1945, p. 343) for the temperature a parcel would have if it were saturated with a mixing ratio equal to the adjusted average surface-layer mixing ratio. The saturation mixing ratio line intersects the sounding temperature curve within a pressure layer if the sounding temperature at the top (bottom) of the layer is less (greater) than the computed temperature. The intersect temperature is determined by linear interpolation by the formula

$$T_{CCL} = [T_{su} (T_{sl} - T_{ql}) - T_{sl} (T_{su} - T_{qu})]/[(T_{sl} - T_{su}) + (T_{qu} - T_{ql})]. \tag{2}$$

The intersect height is

$$H_{CCL} = H_l + (H_u - H_l)\ (T_{CCL} - T_{sl})/(T_{su} - T_{sl}). \qquad (3)$$

The subscripts are: s = sounding curve, q = mixing ratio line, u = upper level, 1 = lower level, CCL = convective condensation level. Williams (1968) has found fairly good agreement between the pressure at the convective condensation level and convective precipitation.

Variable 4. The convective temperature is the surface temperature to which air must be heated before a parcel can rise dry adiabatically to its convective condensation level without ever being colder than its environment. The convective temperature T_C is found as follows: The pressure at the convective pressure level P_{CCL} is

$$P_{CCL} = P_l \exp\left[-\frac{g\Delta H}{RT_v}\right] \qquad (4)$$

where AH is the second term on. the right hand side of (3), T_v is the mean virtual temperature (°K) for the layer bounded by H_1 and H_{CCL}, and g/R = 0.0341416 °K/m. The convective temperature is equated to T_{CCL}, P_{CCL} and the surface-pressure p_s through the Poisson equation:

$$T_C = T_{CCL}\ (p_s/p_{CCL})^{2/7}. \qquad (5)$$

Variable 5. The difference between the convective terwaerature and the 850 mb temperature, T_C-T850, is designed to remove the dependency of T_C, upon season and air mass. This predictor variable, H_{CCL}, and T_C combine moisture and stability. If the air; is dry and/or stable, the H_{CCL} will be higher than if the air is moist and/or conditionally unstable. Likewise, for convection to commence under stable and/or dry conditions, the surface layers must be warmer relative to the layers aloft than if conditions were unstable and/or moist. The difference T_C-T850 gives the relative temperature difference.

Variables 6 through 8 need no additional explanation.

Variable 9. The K-index (George, 1960) combines three measures of temperature and moisture: the stability of the 850-500 mb layer, the moisture at 850 mb and the dewpoint depression at 700 mb. The K-index is expressed by

$$K = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}) \qquad (6)$$

where the subscript d refers to the dewpoint.

Variable 10. The D-index uses the thickness of layers as a measure of dry stability and is given by

$$D = H_{900-700} - H_{700-500}. \qquad (7)$$

If the thickness is large (small) the layer is warm (cold). Thus, for unstable conditions $H_{900-700}$ should be large and $H_{700-500}$. should be small. Large values of D correspond to increased instaBility.

Variables 11. and 12. The Showalter (S) and Lifted (L) indices are both parcel lifted-indices and differ only with regard to the initial starting level. For the Showalter index (Showalter, 1953), a parcel is lifted from 850 mb dry adiabatically to its lifted condensation level thence moist adiabatically to 500 mb. The index is the difference between the 500 mb sounding temperature and the 500 mb lifted parcel temperature (LT). A parcel with average temperature and moisture for the surface to 900 mb layer is used for the Lifted index (Galway, 1956).. The Lifted index has not been calculated for the pilot study because of the requirement that the predicted maximum temperature be used for the surface temperature. The equations for the Showalter and Lifted indices are

$$S = T_{500} - (LT)_{850} \tag{8}$$

$$L = T_{500} - (LT)_{sfc-900} \tag{9}$$

The method for computing the height and temperature of the lifted condensation level is given in Achtemeier and Morgan (1976). Wet bulb potential temperature tables were used in the computer program to compute the temperature of the parcel in moist ascent.

Variable 13. The Boyden (1963) index is similar to the D-index (Variable 10). The Boyden index has been modified for the High Plains by replacement of the 1000-700 mb thickness with the 900-700 mb thickness. The modified Boyden index is given by

$$B = H_{900-700} - T_{700-200} \tag{10}$$

Variables 14-16. The Cross Totals (C), Vertical Totals (V), and Total Totals (T) indices (Miller, 1967) were developed for forecasting severe thunderstorm conditions. They are given by

$$C = T_{500} - T_{d850} \tag{11}$$

$$V = T_{500} - T_{850} \tag{12}$$

$$T = 2T_{500} - T_{850} - T_{d850} \tag{13}$$

Variable 17. The potential wet bulb index (David and Smith, 1971) gives a measure of instability by the difference in the wet bulb potential temperatures between 850 and 500 mb. It is given by

$$I = \theta_{w500} - \theta_{w850} \tag{14}$$

where 0 is the wet bulb potential temperature.

Variable 18. The total energy index (Darkow, 1968) adds potential and kinetic energies to the internal and latent energies included in the potential wet bulb index. This index is, perhaps, best adapted to spatial analysis and, as such, would have application to regions of sloping terrain such as the High Plains. The total energy index E_T is given by

$$E_T = E_{500} - E_{850} \tag{15}$$

where, at any level ,

$$E = c_p T + gz + Lq + V^2/2 \tag{16}$$

Here c is the specific heat capacity of air at constant pressure, z is height above sea level, V is the vector wind speed, and L is the latent heat of condensation.

Variable 19. The Severe Storm Index (SSI) (Williams, 1968) is the sum of the saturation thicknesses from the level of free convection (LFC) to 500 mb and from the lifted condensation level (LCL) to the LFC, where the saturation thickness is the difference between the thickness of the layer calculated from the parcel temperature and that calculated from the sounding temperature. Physically, the SSI combines a measure of the potential buoyant energy of an ascending air parcel above its LFC and the work required to bring the parcel to its LFC from its LCL. An analytical expression for the SSI is

$$SSI = (H_p - H_s)_{500\text{-}LFC} + (H_p - H_s)_{LCL\text{-}LFC} \tag{17}$$

where the subscripts p, s refer to, respectively, the parcel and the sounding. Williams (1968) found good correlation between the SSI and convective precipitation at stations in the Western United States.

Variable 20. The saturation deficit was included in the pilot study at the suggestion of Mr. P. J. Feteris of ERT. It is given by the temperature-dewpoint spread at selected pressure levels ie.,

$$SD = T_i - T_{di} \tag{18}$$

where subscript d refers to dewpoint -
where i - sfc, 900, 850, 800, 700, 600, 500, 400, 200 mb.

Variables 21-22. The wind speed and direction provide simple predictors that should be correlated with low level moisture flow, upper level trigger systems such as the jet stream and/or flow in advance of upper level troughs. These variables are expected to carry information on cloud motions.

Variables 23-25. The 850-500 mb vector wind shear, the 300-700 mb wind direction shear, and the 300-500 mb wind speed shear all address the vertical structure of the horizontal wind. These help identify trigger mechanisms such as upper level troughs and differential destabilization. (The horizontal temperature gradient for a layer is proportional to the vector wind shear).

Variables 26-27 are self explanatory.

b. The Surface Predictor Variables

Table C-7 lists 22 estimator and predictor variables that are derived from fields objectively analyzed from the surface observations. These are being used in a pilot study for Kansas for 7 Junes from 1965-1971. The predictor variables will be correlated with the occurrence or non-occurrence of rain and with the rainfall depth. The correlations will be based on the spatial distributions of predictor variables. Those variables that correlate poorly will be screened out.

Kansas was chosen as the site for the pilot study because 1) the daily precipitation data for Kansas were in an advanced stage of analysis, and 2) the distribution of surface stations is more favorable for objective analyses than are the station distributions at the other HIPLEX sites.

The predictor variables listed in Table C-7 are divided into morning (0600 CST) variables and afternoon (1500 CST) variables. The morning variables complement the upper air predictor variables taken from the morning sounding. The second group is calculated at mid-afternoon, which is the time of maximum thunderstorm frequency for the central and southern High Plains. These should also address the transient trigger mechanisms that initiate convective precipitation systems.

The surface variables mostly are in the moisture and trigger mechanism predictor categories. They complement the upper air predictor variables which mostly address the stability category. Variables (1), (5), in the morning group are indicators of the moisture properties of the air mass present, (2) indicates contrasts between air masses, and (6) indicates local changes of moisture within an air mass. Trigger mechanisms are addressed through subsynoptic scale lifting (3), (7); and the surface reflection of approaching precipitation-producing mid-tropospheric systems (4), (7).

We have attempted to tailor the predictor variables to meteorological conditions at the specific time for which the calculations are made. For example, greater weight is placed upon the pressure field for the morning group than for the afternoon group. Observed surface winds within the nocturnal inversion would not be representative of the winds within the surface layers until after mixing brought about by surface heating has destroyed the inversion.

The afternoon group includes predictor variables that address the thermal properties of air masses when a well mixed boundary layer has developed (3), (10), (11), (13), (14). Variables (1), (3), and (15) are indicators of the air mass present, (2) is an indicator of contrasts between air masses, and local increases of moisture within an air mass are represented in (6), (8), and (14). Trigger mechanisms are addressed through

Table C-7. List of surface estimator and predictor variables.

A. Morning (0600 CST) variables.

1. Surface mixing ratio.
2. Magnitude of the horizontal gradient of the mixing ratio.
3. Vertical velocity induced by the geostrophic wind flow over terrain.
4. The 3 hr (0600-0900) tendency of pressure. Gravity waves on the nocturnal inversion may limit the usefulness of this parameter.
5. The geostrophic wind direction. (8 point compass).
6. Moisture advection by the geostrophic wind.
7. Pressure trough analysis. Here trough axes and low pressure centers are objectively identified and the curvature (second derivative) of the pressure field normal to the trough axes computed. This method helps reduce "noisy" fields that result when the Laplacian of the pressure is taken.

B. Afternoon (1500 CST) variables.

1. Surface mixing ratio.
2. Magnitude of the gradient of the mixing ratio.
3. Wet bulb potential temperature.
4. Divergence of the observed wind.
5. Vorticity of the surface wind.
6. Moisture convergence.
7. Terrain induced vertical velocity.
8. Moisture advection by the observed wind.
9. Pressure trough analysis (see A.7 for description).
10. Height of the lifted condensation level for surface air.
11. Temperature at the lifted condensation level.
12. Cumulative lift. It combines convergence and terrain induced vertical velocity - to give a measure of the vertical displacement at the top of a 1 km deep surface layer over a specified period of time.
13. The 3 hr tendency (1200 CST - 1500 CST) of the surface wind speed. (Suggested by P. Feteris) .
14. Advection of virtual potential temperature. (Suggested by J. Boatman).
15. The direction of the observed wind. (8 point compass).

subsynoptic scale lifting (variables:^, 6, 7, 9, and 12) and the surface reflection of approaching precipitation-producing mid-tropospheric systems by (4), (5), (9), (12).

Many of the surface estimator and predictor variables are calculated using finite difference forms of derivative quantities. Given any element located at a point (i,j) within a two dimensional matrix the adjacent column elements are located by subscripts (j + 1), (j - 1). Also, the adjacent row elements are identified by the subscripts (i + 1), (i - 1).

The surface predictor variables are calculated as follows.

Variables Al , Bl . The method for computing the mixing ratio from the dew point temperature is given in Berry et al . (1945) p. 343.

Variables A2, B2. The magnitude of the horizontal gradient of the mixing ratio in gm/km is given by

$$M = \{[q(i+1,j) - q(i-1)]^2 + [q(i,j+1) - q(i,j-1)]^2\}^{1/2} /2X \qquad (19)$$

where X is the distance between grid points (grid spacing of 104 km is used).

Variables A3, B7. The geostrophic (observed) wind is used to compute the morning (afternoon) terrain-induced vertical velocity. The geostrophic wind is computed using the beta-plane approximation which allows for the latitudinal variation of the effect of the earth's rotation. The terrain values for the Kansas site are specified at 1 degree latitude-longitude intersections (Berkofsky and Bertoni, 1960) and are objectively interpolated to the regular mesh. The vertical velocity w_T in cm sec^{-1} is given by

$$w_T = 100* \{u_g[h(i+1,j) - h(i-1,j)] + v_g[h(i,j+1) - h(i,j-1)]\}/2X \qquad (20)$$

where the terrain height (h) is in meters and the wind components are in m sec^{-1} and U_g and v_g are the geostrophic wind components for variable A3 and the observed wind components for variable B7.

Variable A4 is self explanatory.

Variable A5, B15 - The wind direction is compressed into an 8 point compass with the conversion as follows: 1:0-450, 2:46-90°, 3:91-135°, 4:136-180°, 5:181-225°, 6:226-270°, 7:271-315°, 8:316-359°.

Variables A6, B8. The moisture advection (gm/kg/sec) is calculated using the geostrophic (observed) wind for the morning (afternoon) predictor variable. The advection A is given by

$$A = \{u_g[q(i+1,j) - q(i-1,j)] + v_g[q(i,j+1) - q(i,j-1)]\}/2X \qquad (21)$$

where u , v are the geostrophic wind components in the calculation of A6 and are the observed wind components for the calculations of B8.

Variables A7, B9. The pressure trough analysis is designed as a means of assessing vertical motion independently of the observed winds. It is assumed that an air mass, initially at rest with respect to the pressure field, is accelerated into frictionless motion by the pressure field which is held constant for one hour. The flow into trough axes or pressure centers would necessarily have to be compensated by a vertical component of motion. The average hourly vertical motions are computed for the top of a 1 km deep layer, assuming that the divergence is constant with height.

A computer program has been developed to objectively identify pressure centers and troughs. The "yes" criteria for a trough is that the pressure at a central grid point be less than the pressure at the two adjacent horizontal, vertical, or diagonal grid points. Once a trough has been identified, the maximum of the curvature, measured as the departure of the midpoint pressure from the average of the pressure at the adjacent points, is selected for the vertical motion calculations. The vertical velocity (cm $\sec^{-1}$) is given by

$$w_p = 10\ (pc)\ \Delta t/x^2 \tag{22}$$

where At = 3600 sec and pc is the computed pressure difference in mb. The 10 is a combined conversion factor.

Variables B3, B10, B11. The wet bulb potential temperature θ_e, height of the lifted condensation level (LCL) and temperature at the LCL are all calculated simultaneously. The surface relative humidity is found from the temperature and dew point temperature and the height, pressure, and temperature at the LCL is calculated by the methods outlined by Achtemeier and Morgan (1976). The surface station pressure is obtained from the station height using an estimated conversion factor of 1 mb ~ 10 m height. Then the wet bulb potential temperature is computed from a table that requires station pressure, LCL pressure, and LCL temperature.

Variables B4, B6. The divergence (see^{-1}) of the observed wind and the moisture convergence (gm kg^{-1} sec^{-1}) are computed in the same manner. The divergence is given by

$$D = [u(i+1,j) - u(i-1,j) + v(i,j+1) - v(i,j-1)]/2X \tag{23}$$

where u and v are the wind components.
In the computation of the moisture convergence, u and v are replaced by qu and qv, respectively.

Variable B5. The vorticity (sec^{-1}) is computed from

$$Z = [v(i+1,j) - v(i-1,j) - u(i,j+1) + u(i,j-1)]/2X \tag{24}$$

Variable B12. The cumulative lift is a measure of the parcel vertical displacement over a period of time (Achtemeier and Morgan, 1975)- This analysis uses a simplified form for the cumulative lift. The vertical velocity at the top of a 1-km deep layer, <u>if</u> the divergence is constant throughout the layer, is given by

$$w = -D \, \Delta Z \qquad (25)$$

where AZ is the depth of the layer and D is given in (23). To the vertical velocity is added the terrain-induced vertical velocity. The net vertical velocity is converted to vertical displacement by multiplying by a unit of time, namely 1 hour. Then the cumulative lift is found by summing the individual vertical displacements over a period of consecutive hours (three is being used in the pilot study).

Variable Bl3 is self explanatory.

Variable B14. The virtual temperature is calculated from the surface temperature and mixing ratio by

$$T_v = (T + 273.)\ (1. +1.609q)/(1+q) \qquad (26)$$

where T is the surface temperature in deg. C. Then the virtual potential temperature is computed from Poisson's equation

$$\theta_v = T_v\ (1000/p)^{2/7} \qquad (27)$$

where p is the surface station pressure. The virtual potential temperature gives a measure of the relative densities of adjacent moist and dry air masses and hence an estimate of whether one air mass may undercut and lift the other air mass. The virtual potential temperature advection is given by

$$A_v = \{u[\theta_v(i+1,j) - \theta_v(i-1,j)] + v[\theta_v(i,j+1) - \theta_v(i,j-1)]\}/2X\ . \qquad (27)$$

IV. Climatological Analysis to Identify Significant Predictors

The daily area mean precipitation (0700 CST on one day to 0700 on the next day) was determined for each day of the month of June during the period 1958-1970 for a 29,300 km^2 area surrounding Dodge City, Kansas. These values constitute a basic data sample of 377 and were used in the study of the rainfall-predictor relationships. The daily upper air sounding variables (0600 CST) were correlated with the post-sounding areal precipitation from 0700 on the same day to 0700 on the following day. Correlation coefficients for those variables with correlations greater than .20 are listed in Table C-8.

The dewpoints (Td) at four selected levels are positively correlated with the rainfall and are positively correlated with each other (not shown). Rainfall amount increases as the amount of moisture and the depth of the moist layer increases. The moisture intercorrelations (as given by the dewpoint) between 850 and 800 mb and 600 and 500 mb are high (correlation coefficient .83 and .69, respectively) whereas the intercorrelations between 800 and 600 mb is low (.36). Possible physical explanations for these intercorrelations are 1) the air is drier in the 600-500 mb layer than in the 850-800 mb layer, yet contains more moisture on raindays than on no rain days; or 2) the statistical analysis has isolated part of the mountain-drift precipitation systems where moist air at 600-500 mb is advected eastward over drier air in the surface layers (850-800 mb). The finding that the 700 mb dewpoint was not well correlated with precipitation amounts tends to support the latter explanation.

To avoid the problem of intercorrelation between variables, a stepwise Principal Components regression was performed (the details of this analysis will be described in a later report). The 800 mb Td was the most important of the Td variables (two-tail probability = .26). It would thus seem that explanation 1) above is preferable. However, further analysis and interpretation of the partial regression method is necessary to determine precisely what the intercorrelations mean physically.

The saturation deficits (SD) at 600 and 500 mb are, as expected, correlated negatively with rainfall. It is noteworthy that the saturation deficits for levels below 600 mb fall below the .20 correlation coefficient cutoff. The saturation deficit is defined as the difference between the saturation mixing ratio at the observed temperature and the observed mixing ratio for the same layer. The saturation deficit can be decreased in two ways: 1) the material increase in water vapor exceeds the increase in saturation mixing ratio due to temperature increase, and 2) the decrease in the saturation mixing ratio (proportional to a temperature decrease) exceeds the material decrease in mixing ratio. The saturation deficit decrease in the first instance should correlate well with precipitation increase. The saturation deficit decrease in the second instance should correlate poorly with precipitation increase. The latter condition is expected for post cold frontal flows which may or may not be associated with light precipitation. Bark (1975) found numerous radar echoes on some post cold front days but they were generally small and short-lived.

The pressure-weighted average mixing ratio (WSFCCL) from the surface to the CCL is positively correlated with rainfall. This variable carried much the same information as the 850 T_d and 800 T_d combined.

Table C-8. The relationship between the sounding variables (0600 CDT) and the post-sounding daily precipitation (0700 to 0700 mean areal precipitation) in the Dodge City region (June 1958-70) T_d = dewpoint temperature, SD = saturation deficit, WSFCCL = average mixing ratio, KINDX and CROST = K and Cross Totals indices, respectively.

Variable	Correlation with rain (r)	Partial Regression Coefficient (b^1)	Standard Partial Regression Coefficient (b)	Standard Error of b	t value for b	Two-tail prob. of t
850 T_d	.22	.03	.0066	.0914	.07	.94
800 T_d	.23	.50	.1063	.0940	1.13	.26
600 T_d	.25	.19	.0469	.1238	.38	.70
500 T_d	.27	.30	.0730	.0958	.76	.45
600 SD	-.23	-1249.85	-.0820	.1075	-.76	.45
500 SD	-.23	-3008.26	-.1134	.8003	-1.41	.16
WSFCCL	.24	1.07	.1249	.0883	1.41	.16
KINDX	.24	-.18	-.0646	.0889	-.73	.46
CROST	-.23	-.20	-.0386	.0677	-.57	.57

Multiple correlation .354
Amount of variance explained 12.6%
Sample Size = 337

The K-Index and the Cross Totals index are the only stability indices with correlation coefficients that exceed .20. The more complicated stability indices (Table C-6) were screened from the set by the .20 correlation cutoff. The two indices retained are both heavily weighted toward moisture and are highly correlated with the dewpoint. The correlation coefficients between dewpoint and the K-lndex and Cross Totals are .71 and .86, respectively. The Principal Components analysis shows both indices to be unimportant as the variance is best explained by the moisture variables.

The Principal Components analysis showed that the 800 mb T_d, the 600 mb SD, and the WSFCCL to be the most important parameters in the relationship between the sounding variables and the rainfall. The two-tail probabilities for the significance of these variables are .26, .16, and .16, respectively. If one has prior knowledge of the expected direction of the signs of the coefficients, then the one-tail probabilities would be .13, .08, and .08, respectively. The multiple correlation coefficient was .35 and this value is significant at the .01 probability level.

Although the relationship between sounding variables and the pre-sounding rainfall would not be helpful for real-time prediction, such a relationship, if significant, could provide covariates for evaluation and stratification purposes. Thus, the daily upper air sounding variables (0600 CST) were correlated with the pre-sounding daily areal precipitation from 0700 on the previous day to 0700 on the same day. Correlation coefficients for those variables with correlations greater than .20 are listed in Table C-9. There is a larger number of variables with correlation greater than .20 for the pre-sounding rain (23) than there was for the post-sounding rain (9).

The synoptic picture presented by the physical interpretation of the correlations in Table C-9 is quite consistent with post-cold front and post-squall line temperature and moisture structures. Temperatures through 700 mb are correlated negatively (indicating cold air masses) with precipitation. Dewpoint is still positively correlated, as is the WSFCCL; however, the correlation is significant only at levels above 800 mb. The post-rain air masses may be drier than the pre-rain atmosphere (Table C-8) yet hold more moisture than air masses present in the interim periods between rains. Thus, the positive correlation found for the post-rain dewpoints seems justified.

The saturation deficits (SD) are highly correlated with rainfall. Deficit decreases occur by both moisture increases and temperature decreases. The negative correlations for the height of the convective condensation level (HCCL), the convective temperature (TCC) , and the heights of 0 and -5C levels (HTEM), all reflect the general coolness of the post rain air masses.

Stability indices again fared rather poorly. The K-lndex (KINDX) alone was significantly correlated with rainfall but was screened out by the Principal Components analysis. The positive correlation with the vertical totals (VERT) comes about through the decrease in the 850 mb temperature.

The most important variables are 900 T, 800 T_d, SFC SD, 850 SD, 600 SD, HTEM(0) , and VERT. These variables have two-tail probabilities of significance of .15, .16, .02, .01, .01, .10, and .21, respectively. The

Table C-9. The relationship between the sounding variables (0600 CDT) and the pre-sounding daily precipitation (0700 to 0700 mean areal precipitation) in the Dodge City region (June 1958-70) See text for definition of the variables.

Variable	Correlation with rain (r)	Partial Regression Coefficient (b^1)	Standard Partial Regression Coefficient (b)	Standard Error of b	t value for b	Two-tail prob. of t
SFC T	-.21	.92	.1300	.1470	.88	.38
900 T	-.31	-1.39	-.2936	.2056	-1.43	.15
850 T	-.28	-.08	-.0147	.2132	-.07	.94
800 T	-.29	-.36	-.0682	.1594	-.43	.67
800 T_d	.21	.82	.1760	.1255	1.40	.16
700 T	-.28	-.64	-.0986	.1469	-.67	.50
700 T_d	.24	.32	.0756	.1345	.56	.58
600 T	.26	-.68	-.1688	.1654	-1.02	.31
400 T_d	.23	.20	.0494	.0650	.76	.45
SFC SD	-.36	-2680.13	-.2538	.1073	-2.37	.02
900 SD	-.36	199.85	.0314	.1784	.18	.86
850 SD	-.31	1478.77	.3274	.1319	2.48	.01
800 SD	-.35	268.32	.0541	.1109	.49	.62
700 SD	-.37	846.66	.1047	.1622	.65	.52
600 SD	-.39	-7296.55	-.4824	.1803	-2.68	.01
500 SD	-.22	1628.50	.0618	.0916	.67	.50
HCCL	-.28	-.00	-.0196	.0444	-.44	.66
TCC	-.26	-.04	-.0095	.0508	-.19	.85
HTEM(0)	-.23	.02	.3097	.1880	1.65	.10
HTEM(-5)	-.20	-.01	-.1717	.1708	-1.01	.31
WSF CCL	.21	.72	.0840	.1035	.81	.42
KINDX	.21	.01	.0049	.1592	.03	.98
VERT	.27	1.28	.2190	.1732	1.26	.21

Multiple Correlation = .515
Amount of variance explained = 26.5%
Sample Size = 378

most important variables are SFC SD(-), 850 SD(+), and 600 SD(-). The multiple correlation coefficient was .52 and this value was significant at the .01 probability level. The set of 0600 sounding variables associated with the pre-sounding rainfall has a higher correlation with rainfall than does the set of 0600 sounding variables associated with the post-sounding rainfall; thus, the pre-sounding set of variables are also possible candidates for covariates.

The 0600 and 1500 CDT surface covariates were derived from the basic meteorological variables objectively analyzed to a regular 48 point mesh that covered most of Kansas and parts of Colorado and Nebraska. The covariates were averaged over 9 grid points in the Dodge City area that enclosed the rainfall stations selected for this pilot study. The candidate surface covariates (Table C-7) were correlated with the rainfall from 0700 on the same day to 0700 on the following day. (The sample size was reduced from 377 to 171 since the surface variables were only computed for the period from 1965 to 1970). The results are shown in Table C-10. There was only one variable from the 0600 set of variables that had a correlation of .20 or greater with the rainfall; vertical velocity induced by geostrophic wind flow over the terrain (W_gT). For the set of 1500 variables, there were four variables with correlation coefficients greater or equal to .20. These variables were the surface mixing ratio (qs), the terrain-induced vertical velocity (W_T) , the height of the LCL (HLCL) and the temperature of the LCL (TLCL).

Three of the surface predictor variables that were retained are moisture-related variables: the surface mixing ratio, the height of the lifted condensation level, which decreases with increasing moisture and is negatively correlated to area rainfall, and the temperature of the LCL which increases with increasing moisture, and is positively correlated to area rain. The terrain-induced vertical velocities due to the geostrophic wind (for 0600) and due to the observed wind (1500) were the only trigger-mechanism related covariates retained. For upslope flow to occur in the western Kansas region only an easterly wind component is required. An easterly wind is also expected to advect more moisture into western Kansas.

The results of a multiple linear regression of the rainfall from 0700 on the same day to 0700 of the following day on the five surface variables discussed above are also given in Table C-10. The multiple correlation coefficient was .384 and this value is significant at the .01 level of significance. The most important variables in the multiple regression are W_{gT}, q_s, and TLCL.

The results of a regression analysis of the 0700-0700 rainfall on the combined set of sounding (Table C-8) and surface (Table C-10) variables (a total of 14 variables) are listed in Table C—11. The multiple correlation coefficient was .384 which is significant at the .01 level of significance. The most important variables in this relationship are 500 T_d, 500 SD, WSFCCL, W_{gT}, and W_T.

It is also of interest to determine how well the covariates can distinguish between days with rain and days without rain. Accordingly, the rain days were assigned the value one and the non-rain days were assigned the value zero. The zero-one variable was then regressed on the same li-variable combined predictor set. A multiple correlation coefficient of .50, which is significant at the .01 level of significance, was obtained.

Table C-10. The relationship between the surface variables (0600 and 1500) and the daily mean areal rainfall (0700 on the same day to 0700 on the next day) in the Dodge City region (June 1965-70) For explanation of the variables, see text.

Variable	Correlation with rain (r)	Partial Regression Coefficient (b^1)	Standard Partial Regression Coefficient (b)	Standard Error of b	t value for b	Two-tail prob. of t
w_{gT}	.23	3.80	.1509	.0868	1.74	.08
q	.30	1.30	.1193	.0604	1.98	.05
w_T	.25	4.57	.1044	.0807	1.29	.20
HLCL	-.28	-.00	-.0492	.0950	-.52	.60
TLCL	.33	.68	.1134	.0366	3.10	.002

Multiple correlation = .384
Amount of variance explained = 14.8%
Sample size = 171

Table C–11. The relationship between the predictor variables (0600 sounding variables plus the 0600 and 1500 surface variables) and the mean areal daily rainfall (0700 on the same day to 0700 on the next day) in the Dodge City region (June 1965-70).

Variable	Correlation with rain (r)	Partial Regression Coefficient (b^1)	Standard Partial Regression Coefficient (b)	Standard Error of b	t value for b	Two-tail prob. of t
850 T_d	.25	1.96	.3965	.4448	.89	.37
800 T_d	.21	-.46	-.0966	.1459	-.66	.51
600 T_d	.24	.76	.1783	.1919	.93	.36
500 T_d	.27	-1.46	-.3443	.2602	-1.32	.19
600 SD	-.16	2257.27	.1402	.1794	.78	.44
500 SD	-.22	-16293.45	-.5628	.2967	-1.90	.06
WSFCCL	.29	1.84	.2143	.1281	1.67	.10
KINDX	.28	.40	.1385	.1339	1.03	.30
CR0ST	-.25	2.36	.4425	.3871	1.14	.25
w_{gT}	.23	3.56	.1415	.0907	1.56	.12
q_s	.30	.71	.0656	.0826	.79	.43
w_T	.25	5.29	.1209	.0807	1.50	.14
HLCL	-.28	-.00	-.0158	.1185	-.13	.90
TLCL	.33	.32	.0532	.0470	1.13	.26

Multiple correlation = .472
Amount of variance explained = 22.3%
Sample size = 171

V. Summary and Discussion of Results

A master list of 200 candidate covariates found in the literature survey was reduced to 49 covariates believed to have some applicability to the High Plains summer environment. These included 27 variables taken from soundings and 22 variables derived from objective field analyses. Eight of the 27 sounding variables were not included in the June pilot study, (the layer and total precipitable water, the Lifted Index, and all the wind related predictor variables) but will be included in our subsequent studies. The June pilot study for Kansas tests 41 possible covariates.

In the "post-sounding" precipitation analysis only five covariates were found to explain enough of the variance to be considered as important variables. These are the mean mixing ratio from the surface to the convective condensation level (WSFCCL), the 500 mb dewpoint, the 500 mb saturation deficit, and the terrain-induced vertical velocities based on the morning geostrophic and the 1500 CDT observed wind. The physical significance of these variables has been discussed in the text. In general, the WSFCCL is a measure of the amount of moisture present. The terrain-induced vertical velocity may correlate in two ways: 1) a wind with an easterly component will likely advect more moisture into western Kansas, and 2) the upslope flow may destabilize the troposphere and trigger convective outbreaks. The role of the 500 mb dewpoint and saturation deficit are somewhat harder to assess. It is possible that these variables may reflect the mountain-drift type precipitation system in which moisture is advected eastward over the plains at mid levels.

Equally important to this study is the fact that some variables that are generally highly regarded as covariates were screened out. The surface convergence, surface moisture convergence, cumulative lift, and pressure trough analysis all explained less than 4% of the rainfall variance. Further, no stability-related index was included in the final merged predictor variable set because of low correlation to area rainfall.

These results are consistent with other studies that have found little or no correlation between stability and High Plains convective precipitation. We suspect that the poor correlation between convective precipitation and stability calculated from early morning soundings is at least partly explained by the spatial and temporal transience of the dynamic trigger. This same explanation also applies to the field calculations designed to detect the trigger, namely the convergence-related covariates. It was anticipated that the field covariates calculated for 1500 and perhaps predictive for the 6 hr period thereafter, would partly circumvent the transcience problem since 1500 is near the hours of maximum echo frequency. However, a 3-year study of western Kansas echo populations showed that only 37% of the echoes occurred during this 6 hr period (Bark, 1975).

It is noted that the results concerning covariates are only preliminary at this stage. The use of the hourly precipitation to determine the optimum time to calculate trigger mechanism covariates should increase the amount of variance accounted for in the rain-predictor relationships. The addition of the precipitable water content and the wind speed and direction as predictors should also improve the relationships. These and the inclusion of rainfall patterns, areal coverage, rainfall in surrounding areas as dependent variables and the pattern of field surface predictors as independent variables are the subjects of future investigations. The covariate analyses will be extended to include all HIPLEX sites for all the summer months when the synoptic-rainfall relationships have been optimized.

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APPENDIX D

PRECIPITATION ENHANCEMENT PROJECTS IN THE HIGH PLAINS, A REVIEW

I. General

The National Academy of Sciences has published two extensive reviews of weather modification programs which have been carried out worldwide through the first half of 1972 (National Academy of Sciences, 1966, 1973). Since there is little point to repeating that exposition, this Appendix addresses particularly those programs which are most relevant to HIPLEX, namely projects designed to enhance convective precipitation in the High Plains. A short discussion of the extensive precipitation enhancement experiment in Florida clouds (Florida Area Cumulus Experiment and its predecessors) is included, however, since in many respects, its objectives were similar to the scientific goal of HIPLEX.

Both experimental and operational programs to modify warm season cumuli have been carried out in the High Plains. In some of the operational programs the primary objective has been hail suppression, in some it has been precipitation enhancement, in still others the objectives have been twofold — suppression of hail and precipitation enhancement. Perhaps the most extensive operational program has been carried out in South Dakota where the South Dakota Weather Control Commission began a statewide effort in 1972 (Williams, 1972). Virtually all, if not all, of the operational programs have used silver iodide in an effort to augment precipitation through the ice mechanism.

Experimental programs for the enhancement of convective precipitation have been carried out in the Plains of Texas, Kansas, Oklahoma and South and North Dakota. Almost all projects have used silver iodide as an ice-nucleating agent. Many have also used hygroscopic nuclei in experiments to stimulate precipitation through the coalescence process. The Bureau of Reclamation has sponsored much of this effort.

II. Experimental Programs using Hygroscopic Nuclei

Hygroscopic seeding of High Plains convective clouds has been carried out in several projects in South Dakota, and in projects in North Dakota, Oklahoma, Kansas, and Texas. The most extensive experiments were carried out by the South Dakota School of Mines. These are summarized in Dennis _et al_., 1974.

a. Experimental Projects in the Dakotas

The initial results of the first South Dakota project, Salt Shaker in 1967, indicated that there had been more precipitation from salt-seeded clouds than from unseeded ones. However, later analyses showedthat the initial liquid water contents were higher in the seeded clouds than in the unseeded ones so the results were not meaningful. In Project Cloud Catcher in South Dakota (1969-1970), clouds of all sizes were randomly seeded into the cloud-base updraft by aircraft, some with salt and some with Agl (Dennis et al 1974) . The salt-seeded cases were seeded with 50 kgm of dry salt particles with a median mass diameter of 25 y. This salt mix had to be mixed with coarser salt to prevent clumping. Radar analyses indicated that echoes formed earlier and at a lower level in seeded towers than in unseeded ones. It was concluded by the investigators that, for clouds of a given depth, the seeded cases had larger echoing areas at cloud-base and produced more radar-estimated-rainfall (RER) than the non-seeded cases.

Numerical model experiments carried out on a particular cloud case in 1970 led to the following conclusions (Farley et al ., 1974).

(a) Breakup-induced Langmuir-type chain reaction requires strong updrafts (>10 m/sec) if such a reaction is to have a significant effect on the cloud.

(b) The multiplication process created by breakup can greatly accelerate the production of precipitation water, loading of the updraft, and eventual break-down of the model cloud.

(c) Hygroscopic seeding can, under certain conditions, lead to earlier predominance of the chain reaction.

During the 1971-1972 Cloud Catcher experiments, only convective clouds with updrafts exceeding 10 m/sec were seeded with salt. No significant differences were noted between the radar estimated rainfall from seeded and non-seeded clouds. The investigators conclude that "...sufficient uncertainty remains to preclude adoption of hygroscopic seeding as an operational tool for the northern Great Plains in the immediate future" (Dennis et al., 1974).

The North Dakota Pilot Project (1969-1972) was a precipitation augmentation project which used silver-iodide as the primary reagent. However, in 1972 powdered salt was also released into the cloud-base updraft when the updraft was strong enough, in an attempt to initiate the Langmuir chain reaction. In-cloud measurements indicated no droplets greater than 50 y diameter in unseeded clouds, but large drops were observed in concentrations of 15 per liter a few minutes after seeding with salt. The seeding rate was 5 kgm/min, with 10^{11} particles/kgm generated. No significant changes in precipitation were observed from salt seeding. In-cloud foil impactor data indicated that the precipitation-size particles were ice.

b. Experimental Projects in Oklahoma

A program was initiated in Oklahoma in 1971 (MacCready, 1971) but was terminated after the first year. From mid-August to early October, daytime convective storms of all sizes were seeded. The reagent was an urea-ammonium nitrate-water hygroscopic spray with peak drop concentration at a diameter of 20 y. The seeding was done in the updraft at cloud-base, at a rate of 7-15 gal/min (airspeed of 170 kts). One or two seeding passes were made beneath a medium-sized cloud, in hopes of producing at least one 20-y hygroscopic particle/l No evaluation was carried out.

An unpublished draft report entitled "Southern Plains Skywater Project", describes a randomized seeding test in southwestern Oklahoma that lasted from late April to mid-September, 1972. A network of 50 recording raingages, set out at 10-mile intervals, and an M-33 radar were used as evaluation tools. Both hygroscopic and Agl seeding were used, with randomization by day. The hygroscopic reagent was an urea-ammonium nitrate-water spray which was injected into the updrafts at cloud-base. Normally an echo was present in the cloud when the seeding decision was made. In a comparison of growth ratios (ratio of the median of maximum echo areas to the median of the initial echo area at time of treatment decision), the hygroscopically-treated cases showed larger growth ratios (1.60) than the unseeded cases (1 .10) but smaller than the Agl-seeded cases (2.04). The time between the initial area measurement (within 5-minutes of the treatment decision) and the maximum area was longer in the seeded cases. No significant differences were found in the rainfall, although 51 of the 67 test cases moved over the raingage network. Various other analyses also gave no difference between seeded and unseeded cases.

c. Experimental Projects in Texas

The San Angelo Cumulus Project (Smith et al., 1974) was a randomized project in Texas that ran for three summers, 1971-1973. The initial design was for randomization by day, using both Agl and hygroscopic nuclei. Due to the relative scarcity of seedable days, Agl was eliminated after the first year to enable more salt tests. For hygroscopic seeding the aircraft carried 200 pounds of salt; the median diameter particle was 20-30 u. The release was made into the cloud - base updraft unless the latter was too weak, in which case the seeding was carried out 300 m above cloud-base. Early in the program 100 to 200 pounds of salt were used per cloud, but in 1973 only 100 pounds of salt were used per cloud. The salt particles had peak concentrations in the 20 to 30-p diameter range. They were released at a rate of 40 pounds of salt per minute.

Since there were few raingages in the target area, evaluation was based on cloud-base foi1-impactor data in 1972 and on M-33 radar and foil data in 1973. There were 25 seeded and *2k* unseeded events (clouds) during the 3-year period, with quantitative data available from a total of only 24 clouds. There were insufficient data to determine statistically the effect of salt seeding. However, the data suggested that clouds less than 3-km deep rarely gave precipitation; those between 3 and 4 km gave significant but negligibly small increases when salt seeded; those greater than *k* km would be expected to yield precipitation, but it is unclear whether salt seeding would have any effect on such large clouds. Seeding appeared most effective if the updraft lasted at least 15 minutes.

In the San Angelo area, from two to four clouds could be treated with salt per day if one or two seeding aircraft were available.

d. Experimental Projects in Kansas

The Kansas cumulus seeding project, KANCUP, was carried out during the summers of 1972 through 1972. Both Agl and salt were used as seeding reagents, and seeding took place in the cloud-base updraft. The procedures varied from year-to-year.

It appears that the treatment was not randomized in 1972 and 1973, or at least randomization was not clear in the Project reports (Papania et al., 1972; Papania and Eisenhood, 1973). When cloud tops were warmer than 0 C, salt was used; when they were colder than -5 C, either salt of Agl was used -- and sometimes both. The number of seeding events using Agl greatly outnumbered those using salt, by a factor of 7 in 1973. The predictions of the one-dimensional steady-state model were used to determine seeding potential for the day. Evaluation was qualitative, based mainly on subjective judgement of the response of the cloud to seeding from visual impressions. In general the authors subjectively concluded that salt seeding of cumulus clouds more than 3-km thick caused rain earlier and in greater amounts than occurred in unseeded clouds of the same size. However, this conclusion must be discounted since the project was poorly run for experimental purposes and there are no data analyses to substantiate the subjective judgement of the operators.

In 1974, randomization was by cloud, with a programmed 75% seed, 25% no-seed split (Henderson and Cuddeback, 1974). It is not clear as to how the decision to seed with salt or with Agl was made. A Cessna T-206 was used for the salt seeding. (A second airplane was used for Agl seeding.) The salt particles had a mean diameter of 50 µ and were dispensed at a rate of 80 lb/min. The dispenser held 250 pounds of salt. Of 34 "events", 23 were seeded, 11 not seeded. Three of the seeding events used salt (a total of 750 pounds), and the remainder, Agl. The authors concluded subjectively, from a handful of case studies based on radar, that both salt and Agl increased precipitation but that the effects of salt were short-lived and resulted in no dynamic cloud growth. However, as in earlier years, the evidence presented to substantiate this conclusion is very weak, and it is not possible to evaluate the seeding effect.

III. Experimental Programs Using Ice Nuclei

Clouds of sufficient depth to have the potential for producing significant amounts of precipitation have a high probability of penetrating above the freezing level in the High Plains because of the relatively low temperatures of their bases. Therefore the opportunities for precipitation augmentation through the ice process exist frequently.

Most of the experimental programs to augment convective precipitation in the High Plains have used both hygroscopic and ice nuclei. Virtually all of the experimental programs to augment warm season precipitation in the remainder of the United States have used ice nuclei. With the exception of India, where hygroscopic seeding has been used primarily during the summer monsoon season, ice seeding has been preferred in experimental programs elsewhere in the world (National Academy of Science, 1973).

a. Experimental Programs in the Dakotas

A number of Agl seeding projects were carried out in the Dakotas in the years between 1966 and 1972: the Rapid Project, Grand River Randomized Project, North Dakota Pilot Project, and Project Cloud Catcher. The results of these experiments are summarized in Dennis et al . (1974). In general, the seeding techniques utilized either droppable or fixed airborne flares or airborne generators burning an Agl solution.

In Rapid Project (1966-1968), which utilized randomized crossover target areas, precipitation increases were found on seeded "shower" days (isolated convective clouds) and decreases on "storm" days (widespread convective clouds) (Dennis and Koscielski, 1969) . The reasons for this difference were not clear but contamination of the crossover areas is feared (Dennis et al., 1975)-

In the Grand River Randomized Project (1969-1970), small cumuli were seeded by dropping one or two Agl flares from the -8 C level inside the cloud, or by a few minutes burn of a Agl-acetone generator. During the analysis phases it was discovered that the moisture conditions on seeded and non-seeded days were not comparable, with the control areas and before-seeding target areas being drier on seed days than on no-seed days. Thus, no conclusions as to the effect of treatment could be drawn from the experiment.

The North Dakota Pilot Project (1969-1972) was randomized for "seedable days" where seedability was determined semi-subjectively during the first two years, and was based on the predictions of a one-dimensional steady-state model in 1971 and 1972. Airborne generators which consumed Agl at a rate of about 300 gm/hr* were used to release nuclei in short bursts into the updraft at cloud-base. Based on data from a 67-raingage network, rainfall increases were indicated on days when the 1-D model predicted dynamic seedability. There was a 2.1 increase in rainfall events (raingages showing rain) and a 1.7 increase in average rainfall intensity. An average increase in total rainfall was also observed on seed days. However, it appears that if the 500 mb temperature was less than -15 C, a decrease in rainfall followed seeding, although too few cases were available to be significant. It was estimated from the 4 years of experience that there are about 50 days per summer with dynamic seedability in western North Dakota.

In Project Cloud Catcher (1969-1972) both Agl and hygroscopic nuclei were employed (see Section II). The design of the experiment changed during the life of the experiment, in response to field experience. In 1969 a three-way randomization (salt, Agl, no-seed) was used on "cloud cases" (cloud areas, extending over a period of an hour); in 1970 the same randomization was used, but the experimental unit was the day. In 1971 and 1972, the treatment was determined on the basis of conditions predicted by the 1-D steady-state model. If updrafts of 10 m sec^{-1} were predicted for a 1-km updraft radius, then it was a "salt-seed" day; if updrafts of this magnitude were not predicted, but the model predicted increases in cloud growth of 500 m or more with early freezing, it was an "ice-seed" day; all others were "no-go" days. The randomization was then based on the day with a twcthirds seed, one-third no-seed split.

Clouds were seeded in the cloud-base updraft using 120 gm, 5-minute Agl flares, yielding 5 × 10^{12} nuclei/gm. The time required for the nuclei

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*There is a disagreement in this number in the reports by Dennis et al., 1974 which states 200 gm/hr and by Dennis et al., 1975 which cites the 300 number.

to go from cloud base to -8 C was estimated to be 10 minutes. The seeding was estimated to produce 10 ice particles /l at -8 C. Up to 5 or 6 flares were used per cloud if new cloud growth continued sufficiently long. Beginning in 1971 Agl-NH/41 -acetone generators were used rather than flares.

Evaluation of the data collected in 1969-1970, indicated that seeded clouds had lower first echoes than unseeded clouds. The latter had to be 4 km thick to produce an echo, the former less than 2 km. The seeded clouds also gave greater cloud-base echo areas and increased radar estimated rainfall. (There were too few cases on which Agl seeding was carried out in 1971-1972 to permit analysis.)

Based on experience gained in all of these projects the experimenters (Dennis et al., 1974) concluded that massive Agl seeding in northern Great Plains cumulus could lead to overseeding and a reduction in rainfall, although other authors question the likelihood of overseeding in clouds with perhaps 500 droplets/cm3. Based on the experience gained on these many projects, the South Dakota researchers concluded that the best nuclei-generating technique was the wing-tip generator burning an Agl-NH/41-acetone solution at a rate of 300 gm Agl/hr. The nuclei should be produced in bursts of a few minutes in cloud-base updrafts, or continuously while flying back and forth in the updraft area ahead of a continuous squall line.

b. Experimental Projects in Oklahoma

In the Southern Plains Skywater Project in 1973 a randomized experiment was carried out in southwestern Oklahoma. It was based on a three-way randomization for Agl, hygroscopic, or no-seed treatment. Agl was disseminated in the cloud updraft from wing-tip flares or as droppable flares from the -5 C level. No other details were given in the unpublished report. Although echoes from the Agl seed clouds had the smallest initial area, they had the largest percentage of areal growth of the three treatment classes. There were no other significant results from this program. (See Section lib).

c. Experimental Projects in Texas

The San Angelo Cumulus Project (Smith et al., 1974) was primarily a salt-seeding project as described in Part II. There were insufficient cases to test both Agl and salt seeding to the degree desired. However, during the first summer (1971), Agl seeding was carried out using a Skyfire generator which burned an Agl-NH41-acetone solution into the cloud-base updraft. There were no meaningful quantitative precipitation measurements in 1971 so only qualitative estimates were available. One dimensional model predictions indicated that dynamic growth due to ice-nuclei seeding would occur only a few times each summer. However, light Agl seeding opportunities to produce precipitation embryos occur relatively frequently.

A four-year project carried out in the Big Spring, Texas area (15 April to 15 October 1971-1974) is summarized in Smith and Henderson, 1974. A 12-flare Agl pyrotechnic rack, holding 16- and 64-gm flares, was mounted on each wing of the aircraft. Each flare burned for 8 minutes but multiple firings could be made. Seeding was carried out in the strong inflow areas in clouds which appeared to have sufficient moisture for the production of precipitation. Airmass thunderstorms were usually treated along their trailing edges, squall-line systems in the updraft zones ahead of the line of cells. There was particular interest in large systems which were multicellar and already raining.

Until 31 August 1973 all "seedable" storms were seeded and verification of seeding effects was against historical data. Thereafter, randomization was used on a 75:25 seed:no-seed ratio. Clouds averaged 5~8 miles across and test clouds had to be 20-25 miles apart to prevent the possibility of contamination. A raingage network was available against which an M-33 10-cm radar was calibrated. There was a large variation in the Z-R relationship both within and between storms. There are insufficient data to give results of the randomized program, but the four seeded years all had precipitation above normal for the historical period. It should be pointed out that in 1974 no seeding was carried out in September and October due to high natural rainfall. Without these months, 1974 would have had below normal precipitation.

The authors noted that "overrunning" systems sometimes occurred which gave extensive low cloudiness. This made cloud-base seeding hazardous and made it difficult to locate and to remain in cloud-base updrafts. They recommended consideration of in-cloud or above-cloud seeding when such low clouds exist.

The USAF Air Weather Service carried out a precipitation augmentation project in south-central Texas in July 1971 using AgI seeding (Sax and Cress, 1971). This program was part of a Bureau of Reclamation-directed project designed to help alleviate severe drought conditions in south-central Texas. Thus it was an "experimental" program with no randomization. No measurements were carried out but subjective visual observations of the seeded and unseeded clouds were made by experienced observers. The working hypothesis was to provide dynamic enhancement of cloud growth by sufficient AgI seeding to produce 100 crystals/l in the activation region. The clouds had to be at least 10,000 ft thick, with tops between the -4 and -20 C isotherms, with a turret diameter of at least 2 km. They had to have a hard cauliflower appearance and possess a well-defined updraft with liquid water content of at least 1 gm/m^3. Emphasis was placed on seeding newly-developing eligible turrets in the vicinity of a main tower.

WC-103 aircraft carried racks of 208 droppable 25-gm AgI flares. The clouds were penetrated at the -8 C level or 1000 ft below the cloud top, whichever was lower. Flares were dropped at 200 m intervals. Additional penetrations were made if conditions warranted. More than 1000 seeding penetrations were made into more than 250 cumulus towers.

Sax and Cress stated that localized rainfall increases due to seeding were observed on about 25% of the days but they included the qualifier that instrumentation was not adequate for a scientifically-acceptable analysis of seeding effectiveness. They also concluded that dynamical stimulation of convective clouds is an appropriate approach for conditions in which tropical maritime air supply adequate moisture for the formation of broad, deep, supercooled clouds, and that this condition does occur in southern Texas in late spring and early summer.

d. Experimental Programs in Kansas

The three years of the Kansas Cumulus Cloud Seeding Project (KANCUP) 1972-1974, were briefly described in Section II. No-seed, salt-seed, and Agl-seed tests were carried out.

The 1972 project employed a DC-3 seeding aircraft carrying 32, 64-gm end-burning, 8-minute duration, Agl flares, as well as a salt dispenser. The plan called for two Agl flares per mile in the updraft at the base of towering Cu extending above the -5 C level. When lines or areas of towering cumuli occurred with newly developing towers extending about the -5 C level, 4 Agl flares were burned in the updraft in a continuous line along the edge of the new turrets (Papania et al. , 1972). In the 1973 project the seeding aircraft was a Cessna carrying 24 end-burning Agl flares consisting of 75-gm (burn rate 15 gm/min) and 25-gm (3-5 gm/min) units as well as a salt dispenser. The Agl yielded about 10^{12} nuclei/gm at -8 C (Papania and Eisenhood, 1973). The 1974 project used a Piper Navajo for Agl seeding, carrying racks of 18-gm (2.5 gm/min) and 64-gm (8 gm/min) flares (Henderson and Cuddeback, 1974).

In 1972 and 1973, a qualitative, subjective evaluation was made of cloud response to seeding (based primarily on visual observations). The operators' "evaluation" in 1972 was that "poorly organized and dissipating clouds did not react favorable to the seeding, but the results from the other clouds were very encouraging". In 1973 they stated that on 21 Agl seeding operations (142 cells), 2 clouds gave good response, 6 moderate, 7 marginal, 3 doubtful, and 2 no obvious response. Evaluation of 1974 operations was limited to description of a single case. As in the case of hygroscopic seeding, the KANCUP project was not designed adequately to draw any conclusions regarding the effect of Agl seeding.

e. Single-cloud Experiments in Florida and the Florida Area Cumulus Experiment (FACE)

The Florida experiments are an outgrowth of seeding experiments on individual tropical cumuli in the Caribbean in 1963 and 1965. These early seeding experiments were designed to evaluate the effect of seeding with silver iodide on the dynamics of cumulus clouds. The results supported predictions based on theoretical work and one-dimensional, parcel, numerical model calculations that seeding with an ice nucleating agent would, under certain conditions, stimulate the growth of supercooled clouds (Simpson, et al., 1967).

In 1968 these efforts were moved to Florida and the hypothesis of dynamic enhancement of precipitation from single clouds by seeding with large amounts of Agl was formulated for testing. Randomized seeding experiments on single clouds in 1968 and 1970 reconfirmed the findings of the Caribbean experiments. Moreover, statistical tests indicated that radar-estimated rainfall (which can contain sizeable errors) from seeded clouds was significantly greater than that from unseeded clouds on fair days but not on rainy days (Simpson, et al., 1971).

In 1970 the Experimental Meteorology Laboratory of NOAA (which had also carried out the 1968 and 1970 programs) initiated (on a limited scale in 1970 but still ongoing) a program to study the effect of dynamic seeding on area-wide rainfall. This program (FACE) was designed so as to investigate (a) whether dynamic seeding would induce cloud mergers to produce a larger cloud system and (b) if these mergers result in increased rainfall over a target area.

FACE is a comprehensive program which includes measurement of the physical characteristics of the clouds as well as precipitation measurements. There is a concerted effort to evaluate the effect of seeding on area rainfall. The program is described in detail by Woodley and Sax (1976) and will be covered only briefly here.

The experiment is randomized by day, for days preselected by objective criteria which include one-dimensional steady state model predictions. Seeding is by aircraft into the tops of cloud towers which meet objective criteria for visual and internal cloud tower characteristics. Several pyrotechnic flares are dropped into the cloud along the flight path, burning a few to several hundred grams of Agl during their fall (generally the layer between -12 C and -4C). Operations are the same on "no-seed" days as on "seed" days except that silver iodide is not burned. The individual selecting cloud "subjects" is not informed as to whether or not the clouds are being seeded.

Evaluation of seeding effect on rainfall is based on raingage-adjusted radar estimates. The concept of the "floating" target has been introduced for evaluation purposes, where the floating target is composed of clouds that were seeded and all clouds that merged with them. Also a search is being made for covariates as a means of coping with the high natural variability in rainfall.

Since the program is still in progress, only preliminary evaluations FACE are available (Simpson, J. and W. L. Woodley 1975). Although the results appear promising, the effect of dynamic seeding on rainfall ineitherthe floating target or total target has yet to be resolved.

Perhaps the most disturbing results to date have come from the internal cloud measurements, which indicate (a) frequent significant concentrations of naturally-ocurring ice particles at relatively warm temperatures and (b) no marked differences in cloud characteristics between seeded and non-seeded cloud populations. The latter could stem from inadequate knowledge of the natural cloud processes and/or from inadequate sample sizes. There are also several problems associated with obtaining representative in <u>situ</u> measurements. These studies are continuing also, since they are essential to verifying the physical hypotheses.

f. Seeding Techniques

It is clear from the reviews above that a number of methods are available, and have been used, for Agl seeding of cumulus clouds. These techniques encompass 1) the location from which the material will be released, 2) the technique for generating Agl particles, and the rate at which they are generated, 3) the chemical composition and phase of the fuel.

The basic technique for generating ice nuclei usually is either a pyrotechnic flare or a burner-generator. Flares may be freely "dropped" anywhere in the cloud, end-burning flares may be attached to racks on an aircraft to be fired off one by one, or may be ignited from racks on the ground. Burner-generators require flammable solution (usually an Agl complex in acetone) and may be wing mounted on an airplane or operated on the ground. The ground generators appear to work satisfactorily in orographic conditions where windward-side mountain updrafts carry the Agl nuclei aloft into the clouds, but the nuclei apparently cannot be counted on to penetrate Great Plains cumulus clouds (Schleusener, 1966) .

In a cloud-chamber test of various Agl solutions (Blair et al . , 1973), Agl-Nal, Agl-Kl, and Agl-NH$_4$l were compared. It was found that Agl-NHZ4l was most effective, producing 10^{12} ice nuclei at -5 C. The other solutions required colder temperatures to produce this number of nuclei and also colder temperatures to produce ice crystals. In natural clouds, Agl-NHljl would be effective with cloud tops between -5 and -10 C while the others would not. Furthermore, if released below or in clouds at temperatures above their freezing point, Agl-NH/$_4$l nuclei are less affected by moisture, less hygroscopic, less likely to dissolve, and would be more effective upon reaching their critical nucleating temperature. Therefore, the Agl-NH$_4$l -acetone solution has been preferred recently. Since ammonia is corrosive, stainless-steel generators and fittings are recommended if this solution is used.

The rates at which the fuel (solution or flares) has been burned covers a very wide range. These are usually varied by using larger flares, or multiple firing of flares or generators. There is a consensus regarding the number of crystals that should be generated, but apparently no consensus on the amount of Agl to be burned to achieve this crystal concentration, at least for the formation of precipitation embryos. This is not surprising since very little is known about the rate of dispersion of material in clouds, about the fate of the Agl particles once they are generated (e.g. rate of de-activation), or about the nucleation process itself. However, there does appear to be a general agreement that massive amounts of silver iodide are needed for dynamic enhancement.

Although most experimenters have released materials at cloud-base there is no general concensus with regard to preferred location for seeding, either. Cloud top and near-freezing level seeding have been used as well as cloud-base seeding.

IV. Summary and Discussion

Most of the seeding experiments for augmenting convective precipitation in the High Plains have used both salt and silver iodide as nucleating agents. This is unlike experiments elsewhere in which, with few exceptions, modification of precipitation has been attempted through manipulation of the ice process.

In most of the High Plains experiments, salt-seeding has been with finely-ground salt (20 to 30 μ peak particles diameter). The objectives have been to initiate precipitation embryos (droplets > 50-μ diameter) at a concentration of at least l/l. Seeding has been in the cloud-base updraft, using 100 to 200 lb.salt per convective cell. A cloud suitable for salt-seeding needs to be at least 2, and preferably 4, kilometers in diameter, 3 to 4 km thick, with an updraft of at least 1 m/sec, and a liquid water content of at least 1 gm/m^3. Updrafts of about 10 mps or greater provide the best conditions for hygroscopic seeding because, if the cloud is thick enough, the "Langmuir chain reaction" is likely to occur. Some researchers, believe that significant coalescence precipitation will occur only if the chain reaction occurs but that such powerful clouds would precipitate naturally anyway. Other researchers believe that significant coalescence precipitation can be obtained by salt seeding of growing, convective clouds more than 4-km deep even without the strong updrafts needed for the chain reaction. However, these clouds reach temperatures cold enough to react to Agl seeding, which offers significant advantages to salt seeding.

It. is likely that salt seeding can initiate precipitation embryos in High Plains summertime convective clouds, earlier and lower than would happen naturally. However, there is no enhancement of cloud growth, so only the cloud droplets collected by the precipitation embryos can be realized as precipitation. Moreover the early development of precipitation can result in "water loading" in the lower part of the cloud. This in turn could cause deterioration of the updraft and early development of a downdraft (Farley <u>et al.</u>, 1974). Really useful precipitation can. be obtained only from clouds 3 to 4 km, or more, thick, and especially when the in-cloud updraft exceeds 10 m/sec so that the Langmuir chain reaction may occur. In these cloud cases, the precipitation process could also be initiated by Agl seeding, which logistically offers several advantages.

The potential for hygroscopic seeding could be in the organization of the groups of relatively small clouds into a larger, more organized cloud area, through the early formation of downdrafts in critical regions of the cloud group. The feature (early development of downdrafts) which may be a detriment for augmentation of rainfall from the seeded cell, could be an asset in trying to organize the convection into a better producer of precipitation. However, this theory is <u>highly speculative</u> and requires a great deal of theoretical and, empirical research. A major drawback to salt seeding is the weight of the salt, which means that, either a large aircraft must be used or that only a few cells can be seeded without reloading the dispensers. All-in-all warm rain modification is definitely, still in the exploratory stage. Exploratory research would be worthwhile, if it can be done without interferjng <u>in any way</u> with the execution of the single cloud experiment in any of its aspects, through competition for either resources or cloud opportunities.

The ice seeding can work in two ways. Light to moderate seeding will produce 1 crystal/l at 10°C which will grow to a 50 to. 100-µ precipitation-size embryo in a, matter of minutes (static seeding). Heavy seeding producing perhaps 100 crystals/l in the supercooled layers, will. release large amounts of latent heat quickly and enhance cloud growth (dynamic seedability). (Of course, even light seeding causes some dynamic effect.) Some concern has been expressed by High Plains experimenters that massive seeding in continental clouds could possibly result in overseeding, with much of the condensate going out of the top of the cloud to be carried away by the upper level winds. Dynamic seeding, however, may be effective under conditions in which maritime air infiltrates the High Plains.

A number of techniques for generating and dispersing Agl nuclei have been used. Agl nuclei have been produced by pyrotechnic flares (either droppable or end-burning) or by generators containing Agl-Nal, Agl-Kl, or Agl-NH_4l in an acetone solution. All have shown some evidence of success, but results in actual practice are not completely clear cut. There is some evidence that Agl particles which are released in the cloud-base updraft and then must travel up through the cloud until they reach their effective nucleating level, lose some of their effectiveness as nuclei. Apparently the Agl-NH_4l nuclei are less detrimentally affected. If the seeding is carried out inside the cloud near the effective nucleating temperature, this problem does not arise and all types of Agl seeding agents should prove acceptable.

For growing clouds with cloud tops exceeding -5°C, Agl seeding is to be preferred over salt. For cloud-base seeding, the Agl-NH_4l-acetone generator, with an output of around 300 gm/hr appears a good technique. About 15 gm of Agl nuclei released in the updraft of a smaller cumulus congestus, and about 30 gm in a larger one seem to be reasonable amounts, with additional releases if warranted by cloud growth. Continuous seeding at the rate of 5 gm/min in the updraft ahead of a squall line seems to have been preferred. End-burning wing-mounted Agl pyrotechnic flares are possible substitutes for the generators. If a mixture of 25 gm and 50 to 75 gm Agl flares were mounted in wing racks, the smaller flares could be used for smaller clouds and larger flares for larger clouds. Repeated firings could be made if cloud growth warranted, and successive firings and/or multiple firings in the updraft ahead of squall lines could continue as long as new towers continued to form.

Silver iodide has two main advantages over salt seeding. A smaller aircraft can seed more towers due to the lesser weight of the reagent, and the latent heat of fusion released in the phase change provides a means for enhancing or sustaining the updraft. There appears to be no rationale for using salt except perhaps for clouds not expected to grow significantly above the -5°C level. In most cases such clouds would be expected to produce little rainfall anyway.

If the maritime tropical air moved into the research area, heavy seeding for major dynamic enhancement of the cloud is a reasonable approach. Flares containing 25-gm Agl, dropped into the development turrets at 200-m intervals from around the -8°C level appear reasonable, with repeated penetrations if cloud growth warranted. The flares could also be dropped from above or close to the top of the cloud, but care has to be exercised that the cloud chosen is sufficiently active. The airplane produces a downdraft which can destroy a cloud if it is not sufficiently vigorous.

Finally, a strong growing convective cloud of significant horizontal extent (at least 2 to 4 km), good vertical thickness (3 to 4 km), with cloud-base updrafts of greater than 1 mps and significant liquid-water content (more than 1 gm/m^3) is the best target for seeding to increase precipitation.

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APPENDIX E

REVIEW OF RADAR-RAINFALL MEASUREMENT AND ATTENUATION

I. The.Radar Attenuation Problem

Radar and its application to the measurement of precipitation are among the most critical considerations in the design of HIPLEX. For the "single cloud" phase the problem of precipitation measurement is most critical and a general agreement exists within the Design Group that some combined system, using raingages (or raindrop spectrometers) and digital radar, is desirable if the desired measurement accuracy can be attained. Because of the size of sampling area and gage density requirements,, use of raingages alone may not be feasible.

The two main problems to be addressed here. are: 1) an assessment of the effect of attenuation of 5-cm radar waves on the radar's ability to measure rainfal1, and 2) an assessment of the requirements, in terms of raingage density (gages/mi^2 or mi^2/gage) and numerical techniques, for measuring rainfall for HIPLEX.

Several readily available texts adequately set out the theory of attenuation, practical definitions of terminology, and present reviews of published research on the topic (e.g., Atlas, 1968; Battan, 1973). Reviews on the subject have appeared from which it is clear that no true measurements of 5~cm attenuation have been made. No evidence has been advanced, however, to argue against the validity of the theoretical predictions of attenuation from Mie theory at this wavelength, as long as the attenuating precipitation is liquid water. When hail is present in the precipitation the situation becomes extremely complex. Hamilton and Marshall (1961) estimated attenuation by rainfall at 3, 5, and 10 cm from raingage statistics and concluded that "truly quantitative operation demands 10 cm". For example, they showed that for a gage at 30 mi from the radar having a season's total heavy-shower rainfall of 473 mm, a radar of 5.7 cm would have sensed 349 mm, the difference, amounting to 26 percent, wholly attributed to attenuation.

Harrold (1965) reviewed the attenuation problem and concluded that in the precipitation region of England and Wales where point rainfal1 fates exceeding 50 mm/hr occur only 0.02 percent of the time With rain compared to 0.3 percent in Montreal, a wavelength of 5 cm would be a reasonable choice. Bussey (1950) showed how rainfal1 statistics can be used to generate attenuation statistics. Some of the manipulations Used are interesting and instructive. Ryde (1947) gave an early summary of attenuation and "scattering of centimeter waves by meteorological, phenomena. He covered both gaseous (water vapor and, oxygen) and particulate (cloud, rain, hail, and snow) sources of absorption and scattering.

The basic references on gaseous attenuation are two papers by Van Vleck (1947a; 1947b). These attenuations are wavelength dependent, due to the presence of resonance lines, of oxygen near X = 1/2 cm, and of water vapor at X = 1.35 cm. In the neighborhood of X = 5 cm, there are small but significant sources of attenuation (see Ryde) and can be corrected for by fairly simple schemes. Sirmans (personal communication) has offered software for accomplishing this correction.

Anderson et al. (1947) estimated attenuation at 1.25 cm wavelength, over a 6400 ft path, as a function of rainfall rate estimated from 9 gages along the path. They found that the measured values in db/mile exceeded Ryde's theoretical values by about 50%. The methodology employed in this study can be considered a model for the measurement of attenuation by rainfall. It has not been employed at longer wavelengths because the lower attenuations to be expected over such short paths are not easily detected in the presence of system noise. Medhurst (1965) calculated centimeter wavelength attenuation with Ryde's formula for comparison with measurements. Measurements were available only at wavelengths of 3.2 cm and less. He noted an unsatisfactory agreement between theoretical and measured values, the attenuation exceeding expectations. He proposed for consideration the possibility that the discrepancy might be due to a non-random distribution of drops in the observed volume (clustering). This was suggested to him by results reported by Dingle (1960). Ruthroff (1969) has pointed out some of the difficulties in attenuation-rainfall measurement due to the raingage spacing, but Medh-urst (1969) has shown that these cannot be responsible for the observed discrepancies. More recently, Joss, et al. (1974) estimated 3 cm attenuation by a dual wavelength technique using vertically pointing radars and found excellent agreement with theoretical calculations for moderate and heavy rain rates (> 3 mm/hr). For lighter rain rates the calculated values were less than the observed by about half.

Hitschfeld and Bordan (1954) discussed the problems of attempting to correct the radar return for the effects of attenuation. They pointed out the great sensitivity of the correction error to error in the radar calibration constant. A graph is given in Hitschfeld and Bordan (their Fig. 2) showing total attenuation at 5.6 and 10.0 cm wavelength for several path lengths through rain of varying intensity.

Sims et al. (1964) have proposed a scheme for deliberately undercorrecting for attenuation to avoid the "blowup" described by Hitschfeld and Bordan. It consists of calculating the attenuation from the uncorrected Z data. This approach might be desirable in using 5~cm radar for the Brandes technique for rainfall estimation discussed later.

Mueller and Sims (1969) reported on 16 years of drop-camera measurements which were used to estimate relationships between reflectivity, attenuation and rainfall rate. Measurements were from 8 locations scattered in as many climatic regions. These included Champaign, Illinois; Miami, Florida; Corvallis, Oregon; Bogor, Indonesia; Majuro, Marshall Islands; Franklin, North Carolina; Woody Island, Alaska; and Island Beach, New Jersey. Calculations were made for wavelengths of 10, 4, 3.2, 1.87, 0.86, and 0.43 cm, and results presented in tabular form. Logarithmic regressions are also listed.

Extinction coefficients (in km"') for 5.0 cm (6 GHz) as a function of rainfall rate based on Laws and Parsons rain spectra, can be found in Setzer (1970). A temperature of 20°C was assumed. Wein (1961) described a device for performing the attenuation correction, which required considerable observer judgement for its successful operation.

McCormick (1972) made direct measurements of total attenuation of the signal from airborne beacons at 4.2, 8.5, and 15.3 GHz through rainstorms. These were compared with estimates obtained from reflectivity measurements (at 2.9 GHz) along the path to the beacon, using an empirical Z-A relationship. He found that, provided the precipitation consisted of liquid water, the Z-A relationship predicted the total attenuation well. With hail or a melting layer present the calculated attenuations could exceed the measured total attenuation by factors between 2 and 6. He noted that in some instances attenuation can be significant even at 4 GHz. It is clear from this that successful correction for attenuation requires knowledge about the presence or absence of hail. Of course, estimating A from 5 cm (6 GHz) Z would produce a smaller discrepancy due to hail than estimating A from 10 cm (2.9 GHz) Z.

Dyer and Falcone (1974) calculated attenuation at four wavelengths (including 5.45 cm) and for three temperatures (0, 10, and 18°C) as a function of rainfall rate for four theoretical drop size distributions. For 5.45 cm, they show that at moderate (15 mm/hr) and low (3 mm/hr) rainfall rates a knowledge of the temperature of the precipitation allows a significant reduction in the variability of estimating attenuation from either rainfall rate or Z.

Geotis (1975) estimated 5-cm attenuation by comparing 5-cm and 10-cm echo patterns. He found that attenuations at 5 cm, estimated by assuming the 10-cm reflectivity values to be unattenuated and caused by Rayleigh-size precipitation, exceeded the attenuation calculated from the 10-cm values through a Z-A relationship by large amounts. Attenuations approaching 15 db were noted through the most intense parts of the echoes. He concluded that attenuation of 5-cm radiation by rain was significant and difficult to compensate for. The magnitude of the total attenuation estimates in Geotis[1] study is probably reasonably estimated, but the possible presence of hail in the large thunderstorms he observed may have been a cause of his difficulty in correcting for the attenuation.

Sirmans (personal communication of unpublished results) has made estimates of 5-cm attenuation from digitally integrated 10-cm observations of large storms in Oklahoma. He employed a modified version of the Marshall-Palmer Z-A formula to calculate 5-cm attenuation from 10-cm reflectivity. Figure E-1 shows total attenuation as a function of azimuth for the storm of 6 June 1975 at two elevation angles. Total attenuation exceeds 12 db in the directions of the highest Z values (56 dbz) and is typically 3-5 db along most other radials. More instructive perhaps is Sirman's estimate for the same case of the effect of this attenuation on the total radar estimate of rainfall rate. The total rain flux (in mm hr^{-1} km^{2}) was determined for the S band to be 212,502. The same quantity was inferred to be 151,453 at C band. This is 71% of the "true" value, or an error of 29%. The cumulative precipitation over a period of 3 hrs and 40 min was calculated andshowed peak point values of 127 mm at C band, and 200 at S band. A difference field was also determined and point values of the difference were as great as 92-103 mm. Another example from a different day (12 May 1975) showed the C-band rain flux to be 57% of the "true" S-band value, for an error of 43%.

The presence of hail in the radar beam presents serious complications for interpretation of the echo, due to both scattering and attenuation considerations. The literature on scattering by hail is more extensive than that on attenuation. A thorough review of these would be a major undertaking, unwarranted for present purposes. An important problem in

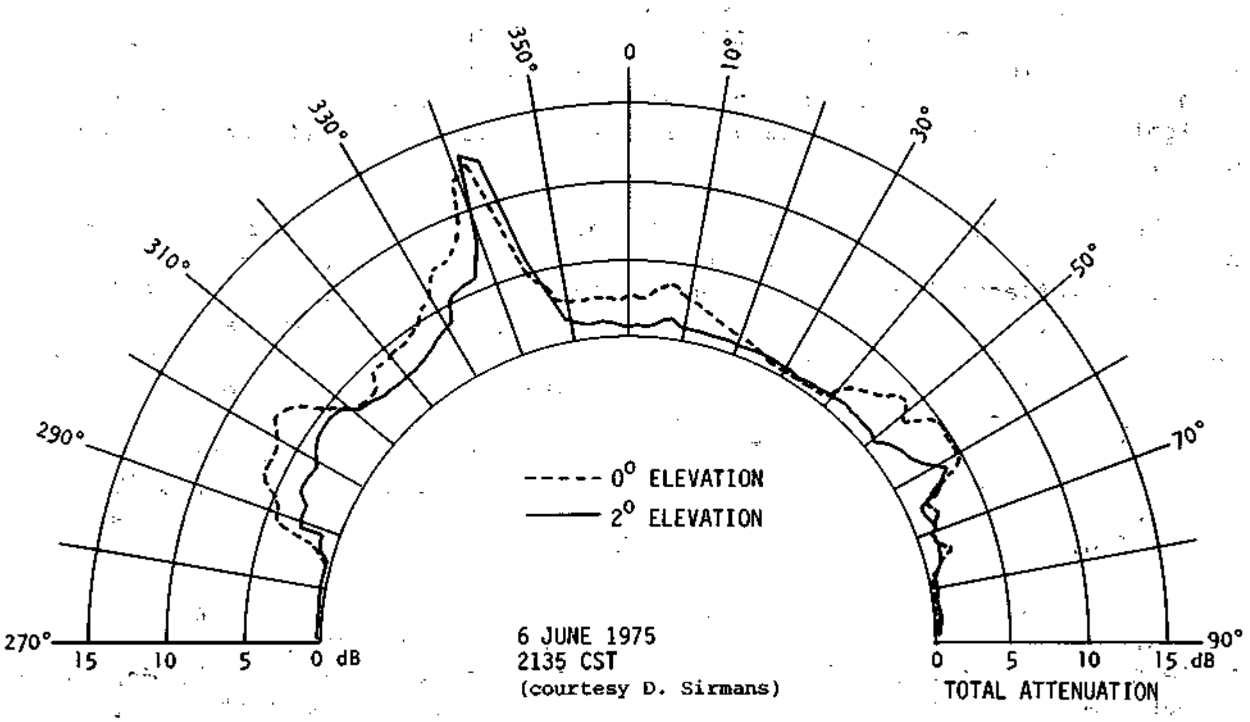

FIGURE E-1 Total attenuation as a function of azimuth (courtesy D. Sirmans).

radar-hail studies is lack of measurements of the hail itself; its nature and concentration. Some representative studies have dealt with hail seen as ice spheres (Herman and Battan, 1961) water-covered ice spheres (Herman and Battan, 1961; Kerker, Langleben, and Gunn, 1951) spongy ice spheres (Battan and Herman, 1962; Harper, 1962; Atlas, Hardy and Joss, 1964) or non-spherical (Atlas and Wexler, 1963; Atlas, Kerker, and Hitschfeld, 1953). Estimates of radar reflectivity based on observed hailstone sizes and concentrations have been presented by Douglas (1960) Douglas and Hitschfeld (1960 and most recently by Dennis *et al*. (1971).

Calculations of attenuation by hail depend on the same assumptions about the shape, composition and concentration of hailstones in storms. Studies of attenuation of ice spheres have been reported by Herman and Battan (1961a), wet ice spheres by Langleben and Gunn (1952), Battan (1971), Battan, Browning and Herman (1970), non-spherical particles by Atlas, Kerker and Hitschfeld (1953), and spongy ice spheres by Battan and Herman (1962).

II. Radar Estimation of Rainfall

As recounted by Atlas (1964) radar meteorology was born in 1941. The early history of weather radar was described at the very end of WW 11 by Maynard (1945). The theoretical background for precipitation detection was available to meteorologists long before suitable equipment was available (Kerr, 1951). Attempts to actually measure precipitation followed. Byers and colloborators (1948) attempted to estimate surface rainfall using geometric measures of radar (10-cm) echoes (heights, areas, volumes, etc.). They found the radar measures did not provide good quantitative estimates of surface rainfall.

Marshall, Langille and Palmer (1947) discussed the theory of rain scattering and showed from measurements that, at 10-cm wavelength, the power returned to the radar by rain was proportional to Z, the sum of the sixth powers of the diameters of the raindrops in unit volume. They showed also a dependence of the returned power on the square of the rainfall rate. They advanced a definition of "radar rainfall" RR in terms of their measured results: R_R= 0.08 Z 1/2, where RR is in mm/hr and Z in mm6/m3.

The raindrop size-distribution measurements which were an essential component of the Canadian radar rainfall studies led to the determination of a functional form for the size distribution of rainfall known as the Marshall-Palmer distribution (Marshall and Palmer, 1948). The suggested form is:

$$N = N_o e^{-\lambda D}$$

This relation, useful for many purposes, both theoretical and practical, has had great importance in meteorology and radar meteorology in particular. It has perhaps been evoked too generally, beyond even the intent of its authors.

Spilhaus (1948) explored some relationships between drop distribution parameters, rainfall rate and radar echo. He used Laws and Parson's (1943) raindrop size distributions, which he found satisfied a simple functional form, to derive a theoretical relationship between Z, the radar reflectivity factor, and R, this rainfall rate.

A comparison of his expression with the power law of Marshall et al. (1947) showed that the simple power law implies unrealistic constraints on the characteristics of the raindrop size distribution.

Twomey (1953) reviewed eight published Z-R equations and added one determined for Sydney, Australia. He emphasized the scatter of measurements about these regressions and the differences between the regressions themselves. His conclusion was that radar was capable of giving only an approximate measure of precipitation.

There are now many references in the technical literature pertaining to studies on the estimation of rainfall by radar. Almost all concentrate on the search for Z-R regression formulae. These formulae, of which there are many (Stout and Mueller, 1968) are only the roughest estimators of precipitation, a factor of two average error in point estimates being typically the best one can expect. This is inevitably so because the radar reflectivity factor, Z, is the sixth moment of the drop-size distribution of which the rainfall rate is approximately the 3.5th. These two moments are not even roughly related except under very restrictive assumptions about the form of the drop size distribution function. In nature, the drop spectrum shape varies; not only from day-to-day or storm-to-storm, but also within each storm (Dumoulin and Gogombles, 1966).

There have been many attempts at predicting the best Z-R regression for a given situation on the basis of storm types (Joss and Waldvogel, 1970), synoptic type (several ISWS publications, among others) and some characteristics of the echo. Meteorological parameters related to evaporation and stability have been used (Cataneo and Vercellino, 1972; Cataneo and Stout, 1968; Cataneo, 1969) to predict the regression. The improvement in accuracy by these methods has not been spectacular.

In spite of the low accuracy of Z-R equations in estimating areal mean rainfall by radar, when compared to the raingage spacing generally available (1 gage per 200-400 mi^2), they usually provide an improvement in the measurement of storm mean or daily total rainfall. Gages are the best estimators of point rainfall, errors due to wind, splash, etc. being estimated at about 10 percent or less. For thundery rain, which is highly variable (short durations, small overall dimensions and sharp gradients), an unreasonably large number of gages is required to estimate the storm rainfall distribution to any desired accuracy (Huff, 1969; Huff and Shipp, 1969; Huff, 1970).

Much interest has fallen on geographical differences in Z-R regressions (several ISWS publications) and there have been derived Z-R regressions for areas with frequent hailstorms (Miller, 1972) and mountain thunderstorms (Foote, 1966). An analysis by Roesli and Waldvogel (1975) established the lower bound (not practically attainable) of accuracy of radar point rainfall estimation at about 15% for 12 hour or longer rain accumulations of over 13 mm. Smith, Cain and Dennis (1975) have developed the most sophisticated of the "Z-R" techniques using a large computer and an optimization scheme. The technique is applicable to monthly or seasonal rainfall estimation, and produces a single optimized Z-R equation for the entire period. As developed, no spatial variations in the equation are considered.

Dual wavelength attenuation techniques have been studied for measuring rain intensity (Atlas, 1954; Rogers and Wexler, 1963; Cartmill, 1963). Attenuation measurements at a single wavelength have also been investigated for use in rainfall measurement (Collis, 1964).

An evaluation of radar measurement of rainfall was performed by Grayman and Eagleson (1970) who concluded that the conjunctive use of raingages and radar was a way of making use of the strengths of each and was superior to either by itself. They recommended the employment of drop-size spectrometers for point calibrations and suggested that wind speed and direction indicators might be useful for determining the lateral drift of the rain. It was also suggested that RH1 information would be useful.

The most recent significant developments in the rainfall measurement problem have stemmed from recognition of the necessity for some combination of gages and radar to optimize measurements. There have been basically two recent developments: a) the cluster technique employed by Woodley et al. (1974) and b) the Brandes (1975) error field technique.

The cluster technique utilizes a small number of sets of closely clustered raingages to determine a Z-R relationship to be applied elsewhere. The basic assumption is that as a storm moves from the clusters to the catchment of interest there is no significant change in its Z-R characteristics. It relies on the presumed existence of an all-day or all-storm Z-R relationship. It is reported that, in a 4800 mi^2 area, this approach yielded an estimate of daily areal rainfall which was within a factor of two 99 percent of the time.

A distinct problem with this approach arises in its application to weather modification experimentation. If a storm passes over the clusters and is then seeded, the seeding, it may reasonably be argued (Cataneo, 1971), will alter or destroy the relationship between Z and R previously established. Some observational grounds for this were reported by Jones et al. (1968). This may be a more serious problem in the dry High Plains area where cloudbases are colder than in Fldrida. Woodley (1971) has argued that the deep warm part of the Florida clouds allows natural cloud physical processes to work to restore the natural precipitation size spectrum following any spectrum changes aloft due to seeding.

The error field technique of Brandes consists of determining, at each gage of a network, the ratio, E, between the gage estimated rainfall, G and the rainfall estimated with radar (R_R) by means of a fixed Z-R regression formula. In practice the radar data are averaged over some area centered on the gage. The values of E at all the gages are then analyzed by an objective technique to produce a correction factor for each point of the radar data field. This amounts to adjusting the radar field to fit <u>all</u> of the gage points. It rejects the search for a Z-R regression entirely. In fact, it assumes that none exists in the sense of previous studies, but that a relationship exists at each point for the time period of the measurement. Justification of the objective analysis of the error field rests on the assumption that the spatial variations of the factors which contribute to the error are all adequately sampled by the available raingage network.

Wilson (1975) has implemented the gage-radar ratio approach of Brandes over the Lake Ontario watershed for IFYGL and estimates daily values to be measured with 10-20 percent accuracy by the technique. This paper is essential reading for its many practical insights into the data handling process.

Some comments on the application of the Brandes error field technique to rainfall estimation follow:

The G/R (gage to radar) ratio, E, can be written

$$E = \frac{G}{R_R}$$

where G is the gage estimate of rainfall rate and R_R is the radar rain rate from the Z-R relationship

$$Z = aR^b$$

from which

$$R = \left(\frac{Z_e}{a}\right)^{1/b}$$

Z_e is the effective Z, given by

$$P_r = \frac{C}{r^2} Z_e$$

C = radar constant
P_r = returned power
r = radar range

so

$$R = \left(\frac{P_r r^2}{Ca}\right)^{1/b}$$

Z_e is related to true Z (neglecting non-Rayleigh effects) by considering the attenuation, A,

$$P_r = \frac{CZ}{r^2} 10^{-0.2} \int_0^r A dr, \qquad \text{where } 10^{-0.2} \int_0^r A dr = \hat{A}$$

$$Z_e = Z \hat{A}$$

and

$$R = \left(\frac{Z \hat{A}}{a}\right)^{1/b} = \left(\frac{Z}{a}\right)^{1/b} \hat{A}^{1/b}$$

if without attenuation the ratio $E = E_0$, then with attenuation

$$E = \frac{E_o}{\hat{A}^{1/b}}; \; E \geq E_o$$

$\hat{A}$ can become very small and if Z_0 is the radar threshold, the attenuation can be such that $Z_e \leq Z_0$.

The gage-radar ratio, E, makes adjustments for a number of effects, most of which are also at work in the cluster approach as well, and which are not neatly independent.

1. The drop spectrum will not, in general, be the spectrum for which the Z-R regression has been derived. The relationship actually chosen is not at all important. This can be seen as follows:

$$\text{if } E_1 = \frac{G}{R_1(Z)}$$

where $R_1(Z)$ is the rainfall estimate from a given Z-R regression, and $E_2 = G/R_2(Z)$ is the error ratio derived by using a different regression,

$$\frac{E_2}{E_1} = \frac{R_1(Z)}{R_2(Z)}$$

which does not contain the gage value. If the R_1 and R_2 are power law regressions

$$\frac{E_2}{E_1} = \left(\frac{Z}{a_1}\right)^{1/b_1} \div \left(\frac{Z}{a_2}\right)^{1/b_2} = Z^{(1/b_1 - 1/b_2)} \left[\left(\frac{1}{a_1}\right)^{1/b_1} \div \left(\frac{1}{a_2}\right)^{1/b_2}\right]$$

a simple function of Z and the parameters of the distributions.

The important result of a particular choice of R(Z) is the range of E which will result. If R is not a reasonable estimator of rainfall rate (say within a factor of less than 5), E could begin to vary over such a range and in so non-linear a fashion as make analysis of the field of E clumsy, if not impossible. This is one of the main concerns about using an attenuated wavelength; the signal can be below or very close to threshold over a gage with a sizeable rainfall rate, resulting in extremely large value of E (in fact, an attenuation of 15 db can occur in very large storms at 5 cm). This can be dealt with, but results in a degradation of the overall system. There is room for further evaluation on this point.

2. There can be differences in the drop spectrum sensed by the radar, which looks at a large volume over the gage, and the spectrum directly over the gage. This can be caused by evaporation, size-sorting in sheared flow, or divergence in the wind flow.

3. There may be melting solid precipitation in the upper part of the beam (bright band, melting hail).

4. There is, in general, a wind field in the lower atmosphere such that at least some of the precipitation in the beam is destined not to fall through the bottom of the beam.

5. There may be strong gradients of reflectivity across the beam. This should be dealt with as described by Rogers (1971). This is a particular case of the general problem of beam filling errors.

6. There may be echoes due to anomalous propagation in otherwise echo-free areas as well as within the precipitation echo. Methods of dealing with this are discussed by Johnson et al. (1975).

7. Ground clutter may be present within the precipitation echo or around it. This problem has been dealt with by Harrold et al. (1974). It may be necessary to relocate some gages to assure estimates of the precipitation in some problematic areas.

8. Nearby obstacles may occult the beam at some angles. This must be determined in advance and some gages relocated to assure adequate sampling of precipitation in such areas.

The gage-adjusted radar rainfall field will have a pattern that differs from the basic radar echo intensity pattern (when a single Z-R regression is used the basic pattern is not altered). It reflects strongly the shape of the gage rainfall pattern. This may be important for using the radar to determine the area-depth curve which Huff (1968) has advanced as a useful tool in weather modification research.

Considering the problems of attenuation correction mentioned in the earlier section, it is interesting at this point to consider the applicability of the undercorrection scheme of Sims et al. (1964) to the E field approach to rain estimation.

The increase in E over E_O due to attenuation alone has been shown above. If the undercorrection is applied to the Z_e field, a new field Z^1, will result such that

$$Z' = Z\ 10^{-0.2 \int_{r_o}^{r_o+s} (A-A')dr}$$

where A^1 is the underestimate of A. The new first-guess rain field will be

$$R' = \left(\frac{Z'}{a}\right)^{1/b} = \left(\frac{Z}{a}\right)^{1/b} \left(10^{-0.2 \int_{r_o}^{r_o+s} (A-A')dr}\right)^{1/b}$$

and the new gage-radar ratio, E', will be

$$E' = \frac{E_o}{\left(10^{-0.2 \int_{r_o}^{r_o+s} (A-A')dr}\right)^{1/b}}$$

or, relative to the uncorrected field, E,

$$E' = E \left(10^{-0.2 \int_{r_o}^{r_o+s} A'dr}\right)^{1/b}$$

which can amount to a considerable reduction of the gage-radar ratio over the uncorrected case. This means, of course, leaving the residual attenuation $(A-A^1)$ in the accumulated rain field, to contribute to the gage-radar ratio. This or a related scheme should prove useful in applying the error field technique in HIPLEX.

III. Suggestions for Research

A need exists for additional research on the use of radar for precipitation measurements in the HIPLEX program. Several suggestions for such research are listed below.

1. A statistical study of the gage-radar ratio

    a) as a simple function of range from the radar, and distance through echo and

    b) examining the effects of different time intervals.

2. A study of the performance of the gage-radar ratio technique with and without correction (total and undercorrection) for attenuation, restricting considerations to areas within echo.

3. With drop-camera or disdrometer data one can calculate: a) the rainfall rate, b) the radar Z, c) the radar rainfall rate from Z through a Z-R relationship, and d) the ratio E as the ratio of a) to c). This will permit study of the basic coherence of the field of E through its time variations at a point. With assumption of steady state, time variations can yield estimates of the scale over which significant changes in E occur. If a network of dis-

drometers is available, the actual spatial differences in E can be determined. Either way, the calculated values of E can be compared to those obtained at the same place(s) by the radar. This will provide an estimate of the contribution to E of the factors not directly related to the drop spectrum over the gage.

4. A study can be performed using the radar and the 1 mi^2 gage mesonetwork data set of Woodley (1 gage/mi^2) to determine the performance of the E field approach as a function of gage density. Woodley's is the only data set believed available for this purpose.

5. Examine the possibility of doing hail mapping with the gage-radar ratios.

6. Examine the possibility of verifying seeding effects on the basis of the gage-radar ratios.

7. Examine the utility of the area-depth curve determined from the gage-adjusted radar rainfall field to evaluate seeding effects.

8. It would be interesting to explore the possibility, and some estimates of the cost, of making measurements of total attenuation of the signal from airborne beacons at 5 cm wavelength, using McCormick's (1972) methods.

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