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THAILAND APPLIED ATMOSPHERIC RESEARCH PROGRAM

Final Report
Volume 1

Program Summary and Recommendations

Submitted to
U.S. Agency for International Development

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16. ABSTRACT

This final report, prepared by the Bureau of Reclamation under the PASA, consists of three volumes. Volume 1 includes a summary of the AARRP structure, the contributions to the AARRP by the U.S. and the Royal Thai Governments, and the institutional development, technology transfer, technical, and scientific accomplishments. Volume 1 concludes with a summary of problems encountered, lessons learned, and recommendations for the future. Volume 2 presents a detailed account of the scientific studies and their findings, and provides the design of the demonstration project (also known as AARRP Phase 2). Volume 3 presents the operations plan for the demonstration project.

Results of the AARRP cloud modeling and field studies suggest that increasing rainfall by static, warm cloud seeding with hygroscopic particles and by dynamic, cold cloud seeding with silver iodide are scientifically promising. A definitive warm and cold cloud seeding demonstration project to quantify the water augmentation potential of these rainmaking techniques in Thailand is warranted and recommended as the next logical AARRP activity. This PASA has provided a design and operations plan for the proposed demonstration project, as well as the equipment needed to carry it out. Training in the operation, maintenance, and use of this equipment for field experiments has also been provided; however, training in the scientific decisionmaking associated with the execution of the required seeding procedures was not completed, and training in the analysis, evaluation, and interpretation of experimental results was only started. As a result, Thai scientists are not yet capable of implementing the proposed demonstration project on their own. Therefore, it is recommended that the demonstration project be implemented *if and only if* the MOAC continues foreign technical assistance to 1) ensure that the demonstration project is carried out in strict accordance with the proposed design following international scientific standards, 2) complete the technology transfer and training started under the AARRP and provide the Thai scientists with a full capability to plan, conduct, monitor, and evaluate rainmaking projects, and 3) transfer the demonstration project seeding technology to Thailand's operational rainmaking program.

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March 1994

UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

DEDICATION

This report is dedicated to His Majesty King Bhumibol Adulyadej, who provides spiritual and scientific leadership for Thailand's program of rainmaking.

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ACKNOWLEDGEMENTS

Many individuals made the AARRP (Applied Atmospheric Resources Research Project) and this report possible, and we want to take a moment to acknowledge them.

We thank USAID/Thailand for their confidence in Reclamation to serve as their technical representative in the execution of the AARRP, and their support of Reclamation in carrying it out. We gratefully acknowledge the guidance and support of former Mission Director John R. Eriksson, under whose leadership the AARRP was conceived and launched, and current Mission Director Thomas H. Reese, III, under whose leadership the AARRP was successfully concluded. Thanks are also due to Mr. Douglas Clark, Mr. David Delgado, Mrs. Thongkorn Hiranraks, and Mr. Kamol Chantanumate, who successfully facilitated intergovernmental project matters and assisted in the resolution of project issues.

We thank Khun Sommai Surakul, Permanent Secretary of the MOAC (Ministry of Agriculture and Cooperatives) and AARRP Director, and Khun Saneh Warit, Director of the BRRAA (Bureau of Royal Rainmaking and Agricultural Aviation) and AARRP Manager, for their support and leadership in carrying out the AARRP. Years of painstaking work by Khun Sommai, Khun Saneh, and their staffs brought the program to where it is today.

A special thanks is due to Khun Metha Rajatapiti, former Director of the RRRDI (Royal Rainmaking Research Development Institute), and the RRRDI Advisory Board and its able Chairman, Dr. Debhanom Muangman, for their vision and dedicated efforts to upgrade Thailand's weather modification program. Their efforts contributed to establishment of the Weather Modification Assessment - Kingdom of Thailand, which, in turn, led to the establishment of the AARRP.

Thanks are also due to our Thai colleagues, who made us feel welcome in their beautiful and exotic country. We are especially grateful for the leadership of Mr. Warawut Khantiyanan, Assistant RRRDI Manager in charge of all AARRP activities, and Mr. Wathana Sukarnjanaset, AARRP Field Operations Director. The success of the AARRP effort to date is due in large measure to their guidance and hard work.

Several Thais scientists became actively involved in helping us with some of the analyses that are presented in this report. Their contributions will be duly recognized in the scientific papers that will be written about the results of the AARRP effort in the months ahead. In the interim, we thank the following persons for their assistance with various aspects of this Final Report:

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GLOSSARY AND ACRONYMS

AARRP: Applied Atmospheric Resources Research Project.

ACRP: ASEAN Cooperative Rainmaking Project.

AgI: silver iodide.

a.g.l.: above ground level.

ASEAN: Association of Southeast Asian Nations.

ATT: Agricultural Technology Transfer Project.

BRRAA: Bureau of Royal Rainmaking and Agricultural Aviation.

Cb: cumulonimbus.

CCL: convective condensation level.

CCN: cloud condensation nucleus.

$CaCl_2$: calcium chloride.

Cold cumulus cloud: a large cumulus cloud whose top rises above the 0 °C level and in which precipitation development by ice particle growth processes is dominant. If the cloud top temperature reaches -10 °C to -25 °C, the cloud becomes suitable for glaciogenic seeding.

Convective cell: the basic element of convective cloud systems, consisting of a single updraft and down draft couplet. The convective cell has been selected as the treatment unit of the 1991 AARRP experiments.

DAS: data acquisition system.

DTEC: Department of Technical and Economic Cooperation.

"Dynamic Seeding": seeding whose primary purpose is to invigorate the internal circulations that sustain the cloud, force the ingestion and processing of more water vapor, leading to larger or more long-lived clouds and increased rainfall.

EEC: Enterprise Electronics Corporation.

EGAT: Electricity Generating Authority of Thailand.

Experimental unit: the convective elements, convective cells, and small multiple-cell convective systems within a circle having a radius of 25 kilometers and centered at the location of the convective cell that qualified the unit for treatment.

FACE: Florida Area Cumulus Experiment.

FOC: AARRP Field Operations Center at the RRFRC.

FOD: AARRP Field Operations Director.

GMS: geostationary meteorological satellite.

GMT: Greenwich mean time.

GPCM: Great Plains Cumulus Model.

GPS: global positioning system.

Glaciogenic seeding: seeding of a cloud with ice-forming chemicals to bring about the conversion of its supercooled water to ice.

IAS: indicated airspeed.

IRIS: Interactive Radar Information System.

"Metwatch": Frequent visual observations of cloud conditions over the AARRP study area, especially the development of convective clouds.

MCM: millions of cubic meters.

MLR: multiple linear regression.

MNR: maximum natural rainfall.

MOAC: Ministry of Agriculture and Cooperatives

MRPP: multi-response permutation procedure.

m.s.l.: mean sea level.

NASA: National Aeronautics and Space Administration.

Non-operational day: a non-operational day is declared by the Field Operations Director when it is desired to give all AARRP personnel time off; generally, the declaration will be made the previous day.

"Nowcasting": a close meteorological surveillance of the project area to determine the weather conditions that already exist and those that are expected to exist in the next 2 hours.

Operational-go day: an operational-go day is declared by the Field Operations Director when convective cloud systems that are likely to be suitable for warm and/or cold cloud seeding exist in the study area, indicating that randomized cloud seeding experiments should commence as soon as possible.

Operational-standby day: an operational-standby day is declared by the Field Operations Director when conditions suitable for randomized seeding experiments do not exist in the study area now, but are expected to develop within the next 2 to 6 hours.

Operational-stand down day: an operational-stand down day is declared by the Field Operations Director when it is desired to suspend operations for the high altitude aircraft crew and the rawinsonde team for the 1300 LST (local standard time) sounding; all other project activities should be continued.

PASA: participating agency service agreement.

PCWG: project coordinator working group.

PDF: probability density function.

PE: precipitation efficiency.

PRF: pulse repetition frequency.

Randomization: a process in experimentation whereby what is to be done to a treatment unit is determined randomly from a set of treatment decisions. Prior to experimentation, the treatment decisions are generated by a mathematical process that ensures that the assignment of treatment is truly random.

Randomized research day: a randomized research day for warm and/or cold cloud seeding is declared after aircraft penetrations of convective clouds establish that suitable conditions are present and that randomized seeding operations are about to begin.

Reclamation: Bureau of Reclamation.

RFC: Regional Forecast Center.

RRFRC: Royal Rainmaking Field Research Center at Chiang Mai Airport.

RRRDI: Royal Rainmaking Research Development Institute of the Kingdom of Thailand.

RSA: resident scientific advisor.

RTG: Royal Thai Government.

Small multiple-cell convective system: a radar echo containing two or more reflectivity maxima or cells, generally within a common echo boundary, but having no horizontal dimension greater than 100 kilometers.

"Static Seeding": seeding to increase rainfall by improving the precipitation efficiency of the cloud.

Study area: the area in northwest Thailand over which randomized seeding operations may be conducted. A map of this area is provided in the main portion of this report.

SLWC: supercooled liquid water content.

SMF: seeding multiplicative factor.

SWCP: the Southwest Cooperative Project that has been conducted in West Texas during portions of the summers of 1986, 1987, 1989, and 1990. This program is continuing.

TAS: true airspeed.

TCu: towering cumulus.

TRMDP: Thailand Rain Making Demonstration Project.

TRMM: Tropical Rainfall Measuring Mission.

TMD: Thai Meteorological Department.

Treatment: The result of the randomization scheme which determines what action is to be taken upon the experimental unit. The treatment will be either to seed convective cells within the experimental unit or to consider the experimental unit as a control and conduct simulated treatment.

Treatment unit: a convective cell within the experimental unit which meets the seeding criteria of liquid water content and updraft speed. The convective cell receives the treatment (actual or simulated) and is the cell in which any treatment effect should first be detected.

TWG: Technical Working Group of the AARRP.

USAID: U.S. Agency for International Development.

VOR/DME: very high frequency omni range/distance measuring equipment.

Warm Cloud: a cumulus cloud whose top never rises above the 0 °C level, and in which precipitation development by collision and coalescence processes is dominant.

WMO: World Meteorological Organization.

WWC: Woodley Weather Consultants.

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1. INTRODUCTION

Since the late 1960s, under the direction of His Majesty King Bhumibol Adulyadej, scientific and technical organizations in the Kingdom of Thailand have been involved with a series of experiments and operational programs to increase rainfall through weather modification. A national program of weather modification was formalized in 1975 through establishment of the RRRDI (Royal Rainmaking Research and Development Institute) under the MOAC (Ministry of Agriculture and Cooperatives). In 1993, the RRRDI merged with the Agricultural Aviation Division of the MOAC to form the BRRAA (Bureau of Royal Rainmaking and Agricultural Aviation). The principal objective has been to increase rainfall through the seeding of clouds over the important agricultural areas of Thailand, where rainfall in some years is less than optimal for crop production. The cloud seeding program is based on a cloud seeding technique that is unique to Thailand: the seeding of warm clouds in a three-step process with exothermic and endothermic chemicals delivered in a specified time and space sequence in an attempt to produce a combination of dynamic and microphysical (static) effects.

Throughout the years, officials responsible for the Thailand weather modification program have attempted to improve its effectiveness by taking advantage of the latest weather modification scientific findings. Thailand cooperates with the WMO (World Meteorological Organization) and the ASEAN (Association of Southeast Asian Nations) in exchanges of information. The results of cloud seeding experiments in other countries have been studied for information on seeding agents, seeding rates, and delivery systems. Thai personnel made official visits to the People's Republic of China in 1984, to the U.S. (United States) in 1985, and to Canada in 1986.

In 1986, His Majesty the King recognized the need for the development and implementation of a more comprehensive scientific approach to the design, operation, and evaluation of Thailand's weather modification program. Accordingly, the Royal Thai Government requested assistance from the USAID (United States Agency for International Development), who agreed to sponsor a visit by a team of experts to assess Thailand's weather modification program and make recommendations for improvements. USAID entered into a PASA (Participating Agency Service Agreement) with Reclamation (Bureau of Reclamation) for implementation of the Thailand weather modification assessment. The PASA to finance the assessment was signed on August 29, 1986.

The team of experts assembled for the visit to Thailand to conduct the assessment consisted of Dr. Bernard A. Silverman of Reclamation, Dr. Stephen F. Lintner of USAID/Washington, Professor Stanley A. Changnon of the University of Illinois, and Dr. John Flueck of the University of Colorado. The team visited Thailand from September 7-26, 1986. The team members observed all phases of Thailand's weather modification program and discussed weather modification technology with members of the Royal Thai Government concerned with water resources and agriculture. On September 21, 1986, the team members had an audience with His Majesty the King, who provided his views on the role of weather modification in Thailand. Details concerning the team visit, as well as background information on the climate of Thailand, the needs for additional water, and the history of weather modification in Thailand, are contained in the team's assessment report entitled, "Weather Modification Assessment: Kingdom of Thailand" (Silverman et al., 1986).

Silverman et al. (1986) recommended a comprehensive 5-year developmental program to improve the scientific and technical capabilities of Thai weather modification personnel through training; additional equipment, including meteorological sensors and computers; and a cloud seeding demonstration project. The Bhumibol Catchment area in northwestern Thailand was recommended as the site for project field studies and experimentation (fig. 1.1).

USAID accepted, in principle, the recommendation for the broad-based technology transfer program to upgrade Thailand's weather modification capabilities. This broad-based technology transfer program is known as the AARRP (Applied Atmospheric Resources Research Program). USAID amended the original PASA with Reclamation to provide for continued planning studies through a visit to Thailand in the summer of 1987 by Dr. Silverman and another Reclamation scientist. Further negotiations among Reclamation, USAID, and the Royal Thai Government led to a second PASA with Reclamation, the current one, for implementation of the proposed AARRP. This 5-year PASA was signed on April 8, 1988. Under a preincurred costs clause, work under the PASA actually began in advance of the signing of the PASA. According to language in the PASA:

> "The purpose of the program is to help develop within the Royal Thai Government an improved capability to design, plan, implement, monitor, and evaluate scientifically-based weather modification projects in Thailand. The program will support improvement in this capability through the transfer of technology, provision of technical assistance, execution of special analyses, provision of scientific equipment, and training.
>
> The project includes short-term measures that will assist and improve present operations and a long-term developmental program to place future operations on a sound scientific basis. The short-term program provides for training in core scientific areas and for assistance in modernizing and upgrading equipment and facilities. The long-term program focuses on institutional development and improvement of a Thai capability to plan, direct, and control rainmaking operations."

Eleven amendments have been made to the PASA. Most of the amendments were primarily for the implementation of financial and/or administrative changes to the PASA. However, two of the amendments also changed the basic goals and objectives of the PASA. The original goal of the project was:

> "The goal of the program is to increase manageable water resources in Thailand through the implementation of a scientifically-based weather modification project on a demonstration basis. The project will lead to improvements in current cloud seeding operations that are conducted to provide limited relief to economic and social impacts of local droughts by seeding promising clouds to increase rainfall over small but critical portions of the country. The program represents a demonstration and test program of improved technology, so emphasis will be placed on evaluation of project results to determine the feasibility of long-term weather modification application as a water resources management technique in Thailand."

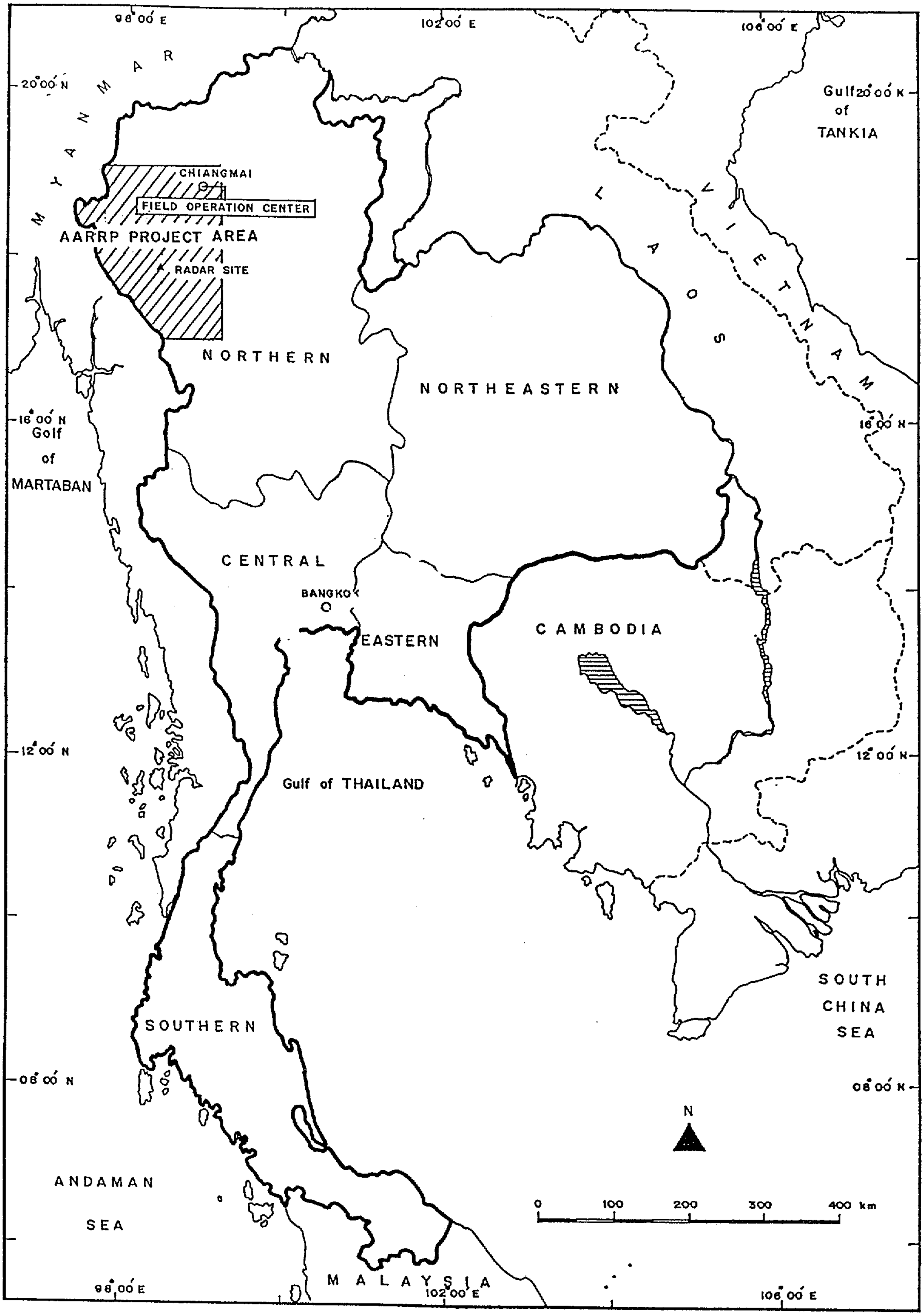

Figure 1.1. - Recommended area of field studies and experiments in Thailand.

As a result of critical delays in the implementation of the project, Amendment 6 to the PASA was executed in December 1989, by which the Project Implementation Plan and Project Goal were changed. The new goal of the project became:

> "The goal of the program is to provide the Royal Thai Government with the capability to conduct a scientifically sound demonstration project to quantify the water augmentation potential of rainmaking in Thailand. The program involves the development of a design and operations plan for the rainmaking demonstration project and the provision of equipment and training to permit its subsequent execution by Thai personnel."

On October 23, 1991, the AARRP PASA was suspended in accordance with the suspension of U.S. economic assistance to Thailand until a democratically elected government was restored to Thailand. The PASA was reinstated on November 1, 1992, by PASA Amendment 8, which made further changes to the Project Implementation Plan and Project Goal. The new and final goal of the project was:

> "The goal of the program is to provide the Royal Thai Government with the capability to conduct a scientifically-sound demonstration project to quantify the water augmentation potential of rainmaking in Thailand. The program involves the conduct of field research and studies leading to the development of a design and operations plan for the rainmaking demonstration project, and the provision of equipment and training to plan and carry out the demonstration project."

Therefore, the AARRP focused on theoretical studies and randomized exploratory experiments to determine which of the physically plausible warm and cold cloud seeding concepts warrant further testing, and the design of a follow-on project (AARRP Phase 2) to demonstrate their feasibility. The goal of AARRP Phase 2 is to quantify the water augmentation potential of promising rainmaking techniques identified under the AARRP (Phase 1) through proof-of-concept experiments in a demonstration project.

It is important to note that, although PASA Amendment 8 further relaxed the Project Goal, the PASA succeeded in accomplishing the design and operations plan for a warm and cold cloud seeding demonstration project as called for in PASA Amendment 6. This accomplishment was made possible by the dedicated, diligent, and cooperative efforts of AARRP scientists from Thailand, and from Reclamation and its contractor, Woodley Weather Consultants.

This final report under the PASA consists of three volumes. Volume 1 includes a summary of the AARRP structure, the contributions to the AARRP by the U.S. and the Royal Thai Governments, and the institutional development, technology transfer, technical, and scientific accomplishments. Volume 1 concludes with a summary of problems encountered, lessons learned, and recommendations for the future. Volume 2 presents a detailed account of the scientific studies and their findings, and provides the design of the demonstration project (also known as AARRP Phase 2). Volume 3 presents the operations plan for the demonstration project.

2. APPLIED ATMOSPHERIC RESOURCES RESEARCH PROGRAM STRUCTURE

2.1 Project Management

The management of the RTG (Royal Thai Government) contributions to the AARRP, as well as the equipment furnished by the U.S., has been and continues to be performed by Thai officials within the MOAC. The Director of the AARRP is the Permanent Secretary of the MOAC. The Manager of the AARRP is the Director of the BRRAA (formerly the Director of the RRRDI).

Overall responsibility for AARRP oversight and planning is provided by a Steering Committee that includes representatives from other agencies. The Chairman of the AARRP Steering Committee is the MOAC Permanent Secretary, who is also the Chairman of the ATT (Agriculture Technology Transfer) Executive Committee. Other members of the Steering Committee include the Director of MOAC's Projects Division, the Director of the BRRAA, and representatives from the Agricultural Aviation Section of the BRRAA, the Bureau of the Budget, the DTEC (Department of Technical and Economic Cooperation), and USAID Thailand. The AARRP Steering Committee met on an irregular basis, mainly to resolve major problems in the implementation of the AARRP. Figure 2.1 summarizes the executive management and organizational structure of the AARRP as of late 1993.

Scientific guidance needed for decisionmaking was provided to the management of AARRP by Reclamation's scientific advisor, who resided in Bangkok as an RSA (Resident Scientific Advisor) during the period October 1988 through September 1990. During this period, the RSA issued AARRP status reports on a monthly basis to document progress and raise issues for resolution by AARRP management. An AARRP PCWG (Project Coordinator Working Group) met on a regular basis to resolve issues within the scope of RRRDI's jurisdiction. The PCWG consisted of the following RRRDI personnel:

- Khun Saneh Warit, AARRP Project Manager
- Khun Sukanya Sakaew, Chairman and Coordinator of Research
- Khun Song Klingpratoom, Secretarial Staff
- Khun Kwanchai Tawamongkol, Coordinator of General Administration
- Khun Prasert Kosalyawit, Coordinator of Project Administration
- Khun Ratana Ratanamalaya, Coordinator of Technical Operations

2.2 Project Personnel

The organization of the Royal Rainmaking Section of the BRRAA (formerly and still known as the RRRDI) is a matrix structure; consequently, the AARRP has been made up of people and support from all four of the divisions shown under the Royal Rainmaking Section on figure 2.1. Figure 2.2 lists RRRDI personnel who were working on the AARRP during the 1993 field season. Some of these individuals are listed more than once on figure 2.2 because they had responsibilities for more than one project task.

2.3 Technical Studies

In 1990, the AARRP Steering Committee appointed a Technical Subcommittee to oversee the research and evaluation aspects of the project. This subcommittee formed a Technical Working Group to begin work on the AARRP hydrometeorological and seeding design studies.

Scientific expertise was sought and secured from local universities. The Thai scientists appointed to the technical working group were:

Thai Scientists	Specialty	University
Dr. Jeimjai Kreasuwun, Leader	Physics	Chiang Mai
Dr. Charanai Panichjakul	Chemistry	Kasetsart
Dr. Nunta Vanichsetakul	Statistics	Kasetsart
Dr. Sutat Weesakul	Mathematics	Chulalongorn

This group was guided in the studies by Reclamation Scientific Advisor, Dr. Bernard A. Silverman. The group worked on project related studies from late 1990 into early 1992, when the RRRDI students returned from their long-term training. After their return, the technical working group was disbanded.

During 1993, an AARRP analysis and evaluation team was formed to work on studies needed for the design of the demonstration project, that is: 1) cloud modeling studies, 2) rain analysis and statistical evaluation studies, 3) sonde analysis and verification studies, and 4) radar analysis studies. The team consisted of:

- Khun Warawut Khantaniyan
- Khun Wathana Sukarnjanaset
- Khun Rachaneewan Talumassawatdi
- Khun Song Klingpratoom
- Khun Prinya Sudhikoses
- Khun Sommart Daengjai

Reclamation and Reclamation contractor scientists provided guidance and training to the team members to prepare them for work that will be needed in the future to analyze and evaluate the demonstration project.

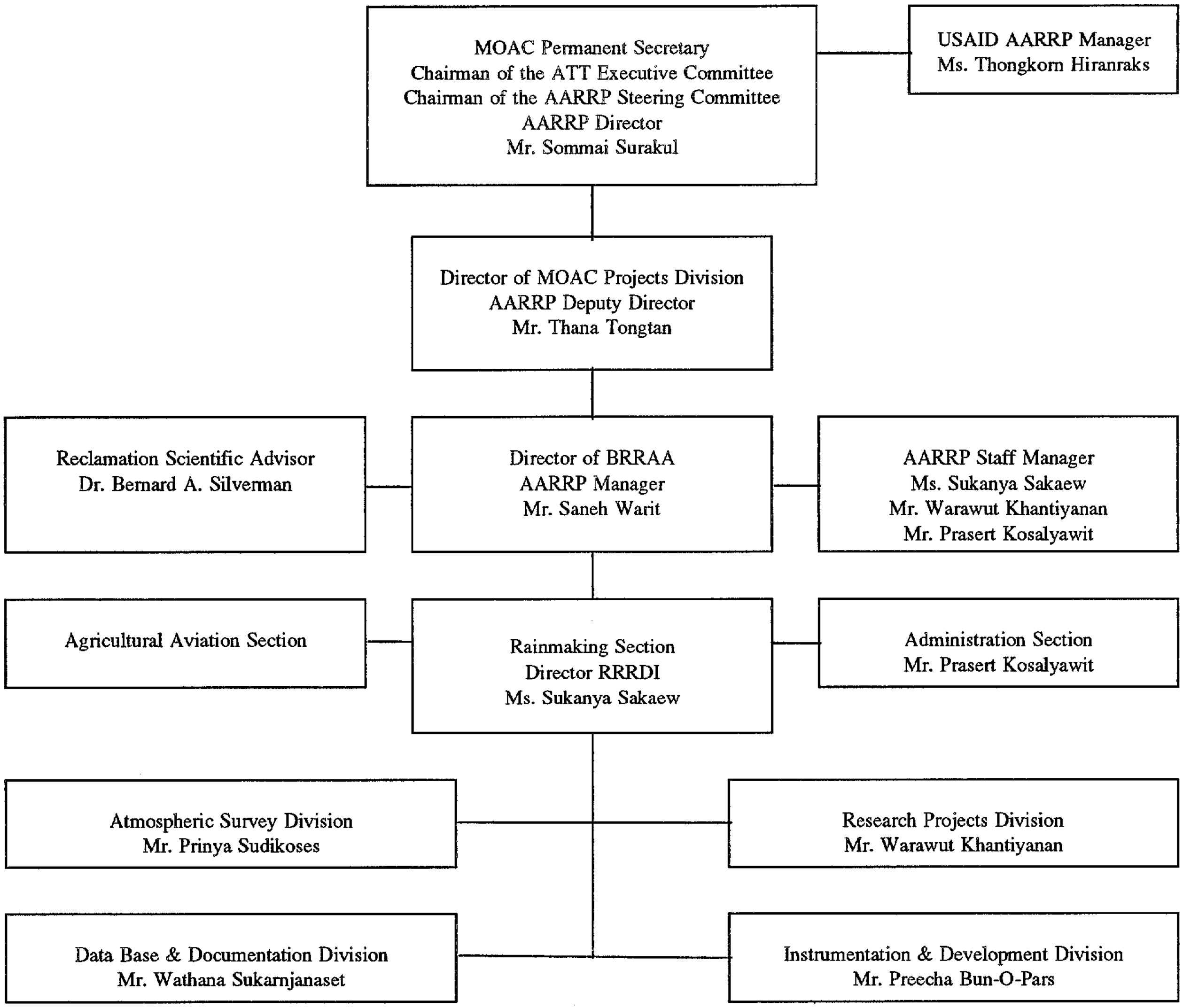

Figure 2.1. - AARRP executive management and organizational structure.

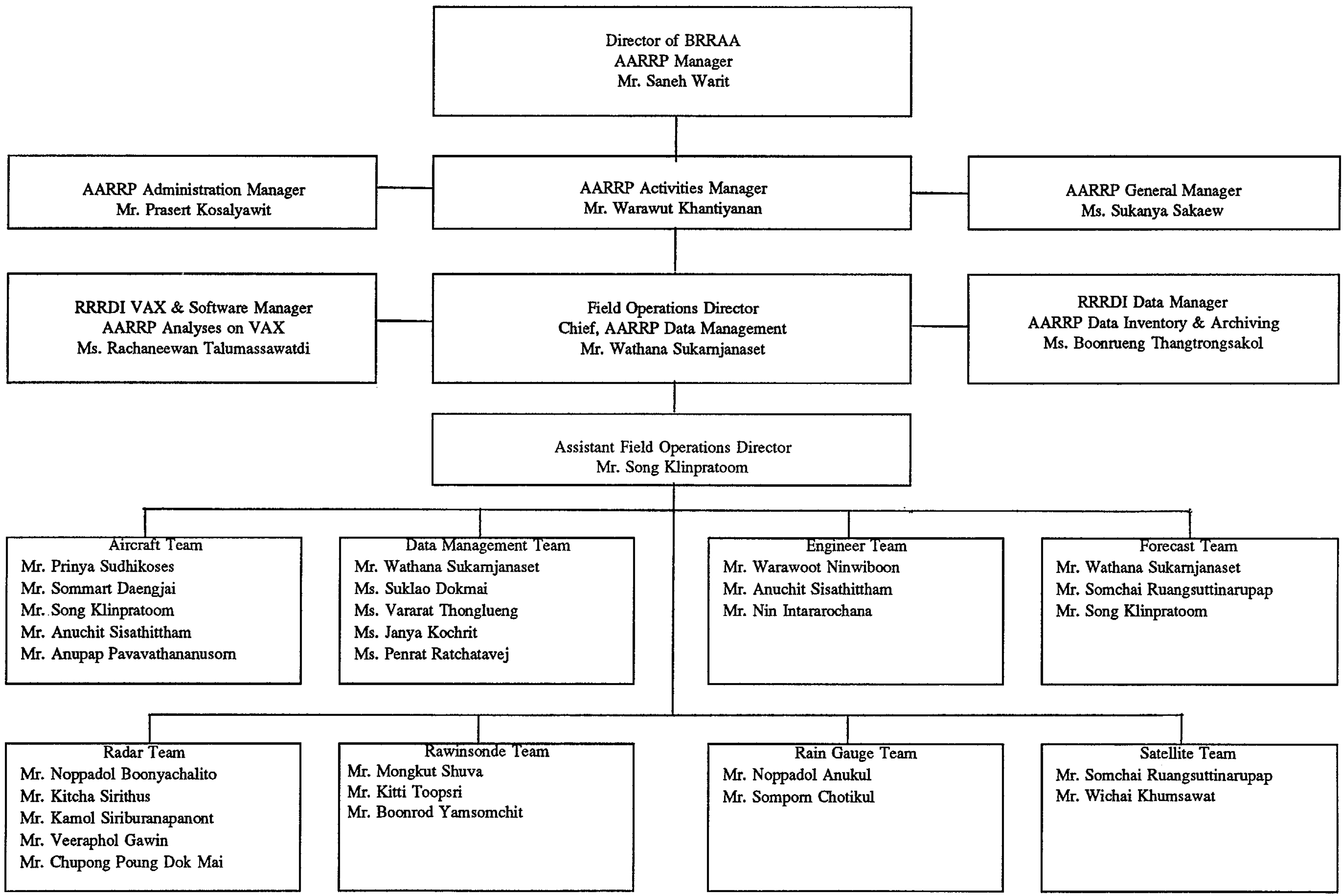

Figure 2.2. - RRRDI participants in the 1993 AARRP field season.

3. CONTRIBUTIONS BY THE ROYAL THAI GOVERNMENT

The RTG has been and continues to be primarily responsible for the provision of personnel and facilities, and for the collection and quality control of AARRP data. The RTG was also responsible for the execution of cold and warm cloud experimental seeding and modeling studies, performed under the guidance of foreign experts. This section provides a summary of the major contributions of the RTG to the AARRP, both for Phase 1 and the start of Phase 2.

3.1 Financial Contributions

The RTG has committed a total of 222,926,800 baht ($8,917,072) to the AARRP for the period 1988-1995. USAID's support to the RTG for the AARRP ends in June 1994; thus, the RTG has already made a financial commitment to Phase 2 of the AARRP. The RTG resources provided, and the related financial costs for the 1988-1995 period, are summarized in table 3.1. An estimated 11,182,240 baht (about 30 percent) of the 1994 budget, was used during Phase 1, leaving 24,631,020 baht in 1994 for Phase 2. This budgeting results in a total of 152,926,800 baht ($6,117,072) for Phase 1 under the PASA, and an RTG commitment of 70,000,000 baht ($2,800,000) for starting Phase 2 of the AARRP. In addition, the RTG obtained 3,750,000 baht ($150,000) in loan money from USAID for the purchase of a GMS (geostationary meteorological satellite) system.

The RTG's financial contribution covers Thai personnel salary, per diem, and travel costs; the multi-year lease of a high-altitude research/seeding aircraft; warm cloud seeding aircraft and helicopter costs; seeding equipment and chemicals; the purchase of new equipment and ground vehicles; vehicle operations and maintenance; installation of new field facilities; equipment spare parts and maintenance; expendable supplies; and other miscellaneous operating expenses.

3.2 Project Personnel

Most of the personnel working on the AARRP were from the RRRDI. As with any multi-year project, the personnel changed from year-to-year because of the completion of long-term training and transfers within RRRDI projects or departments. Some work assignments changed within the AARRP. The number of Thai people working on the AARRP during the PASA period remained fairly constant. During 1993, about 30 people from RRRDI were assigned to work on the AARRP (see figure 2.2). Other personnel who participated on a part-time basis during the 1993 field season were the crews for two warm cloud seeding aircraft and a helicopter from the AAS (Agricultural Aviation Service), and the crew for the high-altitude research/seeding aircraft from Thai Flying Service. Assistance was also received from meteorological forecasters and rawinsonde technicians from the TMD (Thai Meteorological Department) regional center in Chiang Mai.

3.3 Facilities and Equipment

The RRRDI (Rainmaking Section under BRRAA on figure 2.1 under section 2, **APPLIED ATMOSPHERIC RESOURCES RESEARCH PROGRAM STRUCTURE**) is housed in a permanent center constructed on the campus of Kasetsart University in Bangkok. This facility includes a two-story office complex and storage facilities for equipment and chemicals.

A temperature controlled and power regulated computer room was developed within the RRRDI office complex. Most of the scientific analyses for the AARRP are performed with USAID provided computers located in this room.

The RTG provided all seeding chemicals and delivery systems. The cold cloud flare rack system, purchased from AI (Atmospherics, Inc.), was a standard flare rack for ejecting 20-millimeter cloud seeding flares. Figure 3.1 shows the flare rack ready for mounting on the high-altitude seeding aircraft. The AgI (silver iodide) pyrotechnic flares purchased for Thailand were the AI model EJ-20-E-20 type FA6, which have dimensions of 20 millimeters diameter by 120 millimeters length. This flare is a chlorinated formulation, strongly hydrophilic, with a fast nucleation rate. These dropable flares contain 20 grams of AgI and burn at a rate of 0.5 gram per second. Although the RTG uses various hygroscopic chemicals for their warm cloud seeding operations, only the chemical $CaCl_2$ (calcium chloride), which was factory bagged, was used on AARRP Phase 1 warm cloud studies.

In the past, RRRDI had no aircraft of their own for conducting cloud seeding operations, and had to obtain them from the AAS. However, the recent reorganization that placed RRRDI and AAS both under the BRRAA, should make the coordination of the warm cloud seeding aircraft, helicopter support, and air crews needed for Phase 2 of the AARRP easier. Figure 3.2 shows a CASA aircraft from the AAS that has and will be used for the AARRP's randomized warm cloud seeding operations.

Because the AAS does not have a high-altitude pressurized aircraft, the RTG entered into a 3-year lease with Thai Flying Service for an Aerocommander 690B twin-engine turboprop aircraft (shown on figure 3.3). This aircraft was fitted with an RTG-procured dropable flare system for the on-top seeding of cold convective clouds, and a cloud physics data acquisition system provided by USAID. The lease of this aircraft has been extended by the RTG through 1995.

In 1990, the RTG constructed a radar research site within the AARRP study area near Omkoi, about 120 kilometers south-southwest of Chiang Mai. The USAID-provided Doppler weather radar system was installed at this site during the summer of 1991. This permanent site is also used as the base of operations for servicing the automatic recording rain gauges. In 1993, the use of this site was expanded to include an instrumented TMD weather observation area, an upper air observation capability, and a NASA (National Aeronautics and Space Administration) GMS ingest and display system. Figure 3.4 shows a view of the radar site from the air. Figures 3.5 and 3.6 show photos of the radar antenna tower and control building, and radar system control room, respectively. Figure 3.7 shows the standard surface meteorological observation installation, and figure 3.8 shows the GMS antenna installation at the radar site.

Figures 3.9 and 3.10 show the AAS helicopter used for the installation and servicing of the AARRP's recording rain gauge network at one of the fenced rain gauge sites, and the technician checking the gauge calibration. RRRDI personnel built and installed fences for about 50 sites; NASA provided the recording rain gauges under an agreement where RRRDI provides copies of the recorded rainfall data to NASA for their TRMM (Tropical Rainfall Measuring Mission). Figure 3.11 shows AARRP personnel downloading recorded rainfall data using a data translator and a personal computer.

A field operations center for the AARRP was established in 1991 at Bhumibol Dam, about 170 kilometers south of Chiang Mai. The building used for this center was owned by the EGAT (Electricity Generating Authority of Thailand). The operating base for the AeroCommander 690B research aircraft was established at the Tak airport, about 45 kilometers farther south-southeast from Bhumibol Dam. Problems were encountered with both logistics and communications at these facilities; consequently, the AARRP field operations center and the aircraft operations were moved to Chiang Mai after the close of the 1991 field season.

In 1992, the AARRP's field operations center was combined with BRRAA's field research center on the property of the TMD's regional center next to the Chiang Mai airport. Figure 3.12 shows the front side of the Chiang Mai Royal Rainmaking Field Research Center, with some of the AARRP staff. Both the AeroCommander research aircraft and the CASA warm cloud seeding aircraft were based at the Chiang Mai airport close to the Field Operations Center. These changes had a positive effect on conducting AARRP field operations. Figure 3.13 shows the AARRP project area with the location of the radar site and Field Research Center.

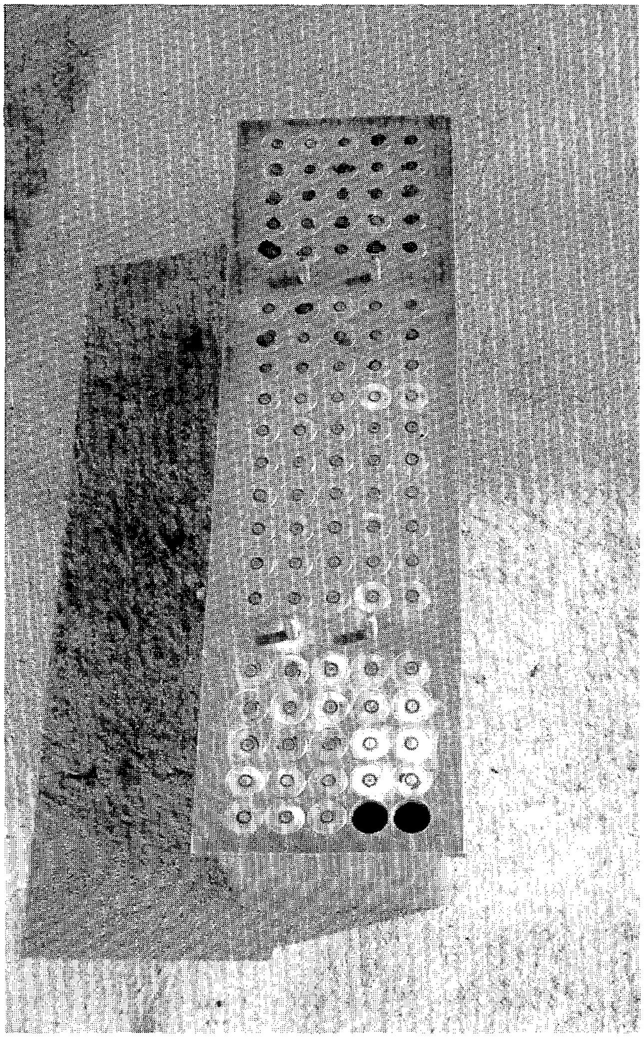

Figure 3.1. - Cold cloud seeding flare rack.

Table 3.1. - Royal Thai Government financial contributions to the AARRP (figures are in baht; 25 baht = 1 dollar U.S.).

Project Element	1988	1989	1990	1991	1992	1993	1994	1995	Total Baht
1. Personnel salary	1,796,000	2,240,000	2,623,000	3,286,000	3,658,000	984,960	1,036,200	1,092,000	16,716,160
2. Flight pay				189,600	189,600	189,600	189,600	189,600	948,000
3. Per diem and travel	678,000	780,000	2,755,000	2,807,000	2,832,000	4,526,100	4,526,100	4,526,100	23,430,300
4. Core training (PD&T)	553,000								553,000
5. Long-term training (tickets)			100,000		100,000				200,000
6. Research & seeding aircraft			4,320,000	7,560,000	23,605,000	11,880,000	12,600,000	13,320,000	73,285,000
7. Helicopter (rain gauges)			1,500,000	3,000,000	3,500,000	3,500,000	3,500,000	3,500,000	18,500,000
8. Radar building			2,939,600						2,939,600
9. Project vehicles		1,031,000				445,700	518,200	603,280	2,598,180
10. Cloud seeding agents			4,294,000		6,926,000	5,891,100	7,069,400	8,483,400	32,663,900
11. Automatic rain gauges		130,300	150,000	150,000	150,000	98,700	100,100	101,700	880,800
12. Rawinsonde systems			1,395,000	3,620,000	1,476,000	2,173,400	2,173,400	2,173,400	13,011,200
13. Radar spare parts				1,599,520	815,800			7,000,000	9,415,320
14. Test equipment				1,548,000	1,609,700	750,000			3,907,700
15. Data comm. network				1,053,700		500,000			1,553,700
16. Equipment maintenance	306,200	851,400	1,657,000	2,421,280	3,684,200	500,000	550,000	605,000	10,575.080
17. Computer supplies/maint.					1,108,800	2,538,600	2,242,460	2,466,700	8,356,560
18. Miscellaneous						132,000	433,000	433,000	998,000
19. Telecomm system lease						644,700	874,800	874,800	2,394,300
Totals	**3,333,200**	**5,032,700**	**21,733,600**	**27,235,100**	**49,655,100**	**34,754,860**	**35,813,260**	**45,368,980**	**222,926,800**

Figure 3.2. - CASA aircraft used for warm cloud seeding studies on the AARRP.

Figure 3.3. - AeroCommander 690B aircraft used for cold cloud exploratory studies on the AARRP.

Figure 3.4. - Aerial view of AARRP Doppler radar site.

Figure 3.5. - AARRP radar antenna tower and control building.

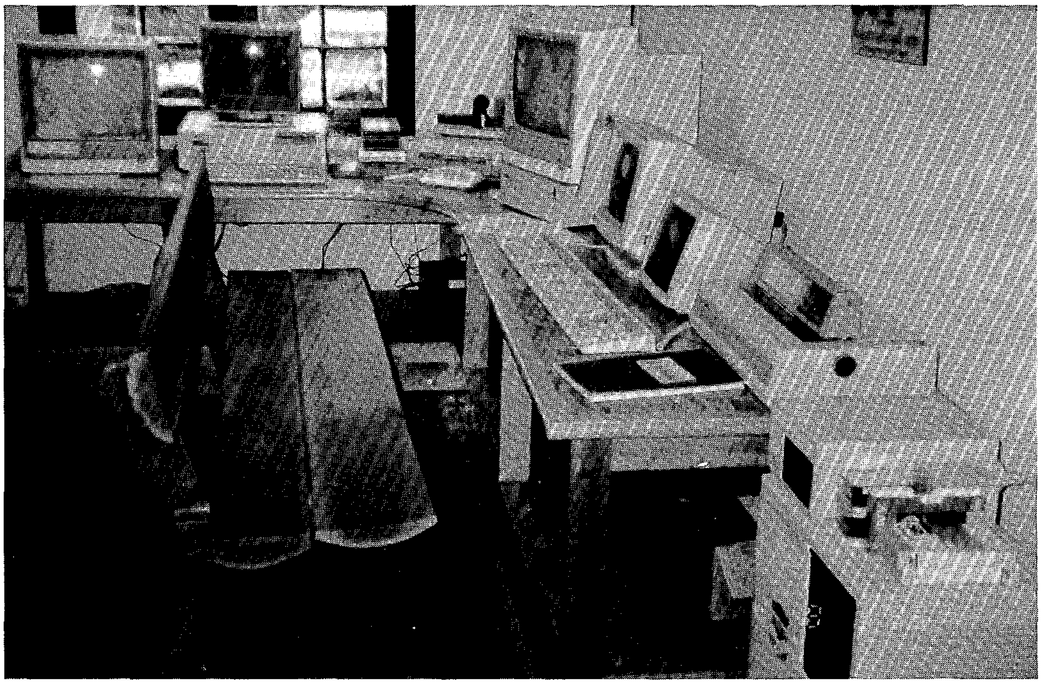

Figure 3.6. - AARRP radar system control room located in the control building.

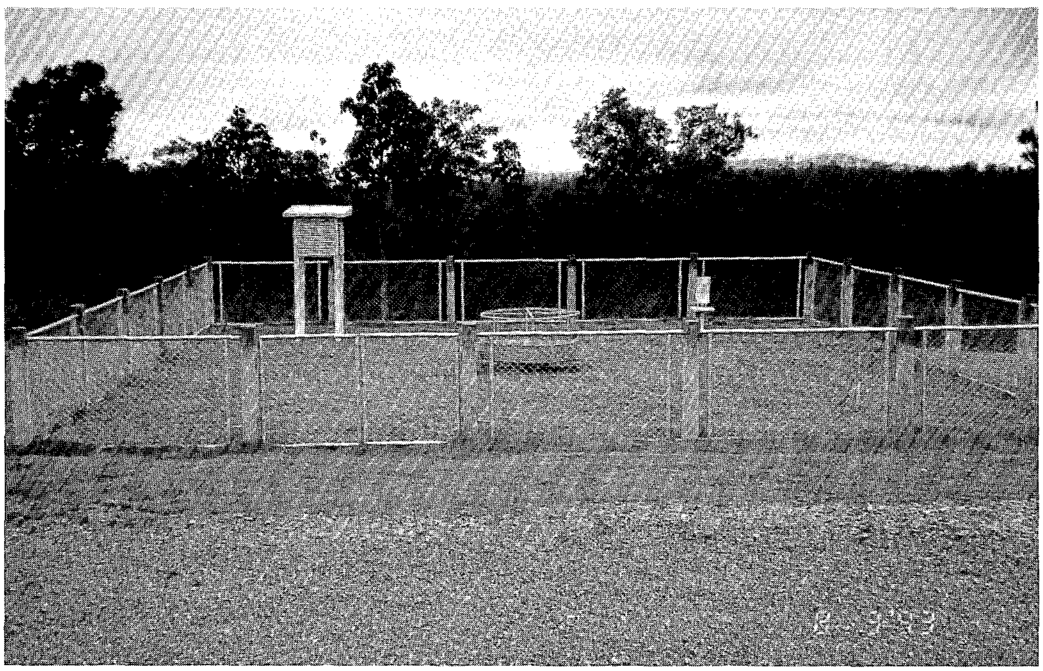

Figure 3.7. - Surface meteorological observation area at AARRP radar site.

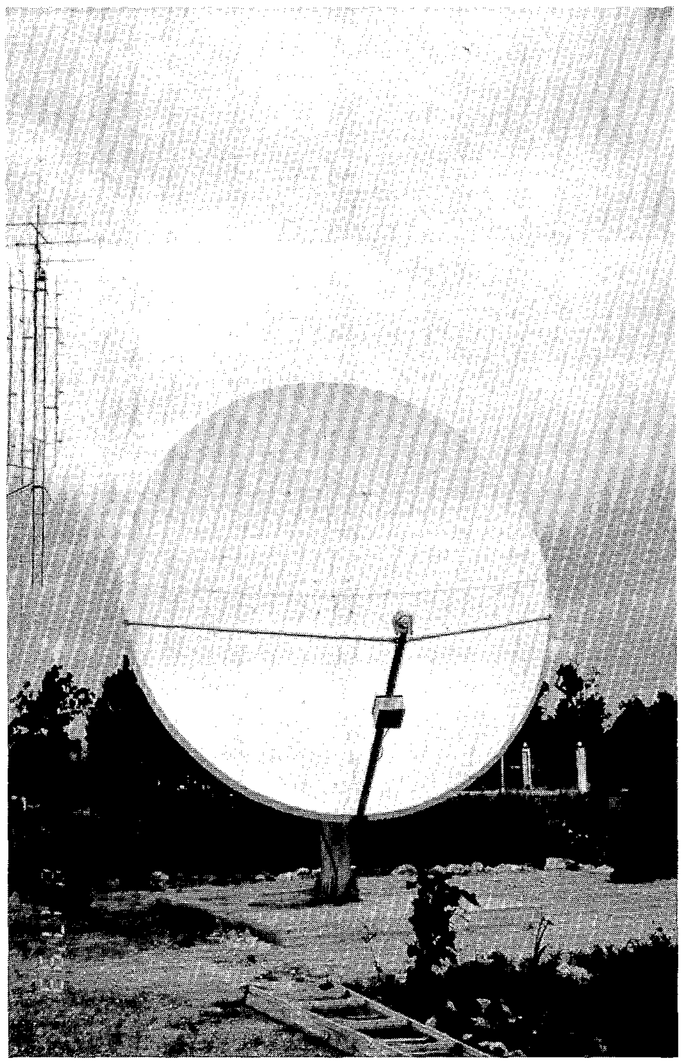

Figure 3.8. - Geostationary Meteorological Satellite antenna installation at the AARRP radar site.

Figure 3.9. - Remote rain gauge installation with the helicopter used to service the rain gauge network.

Figure 3.10. - Rain gauge technician checking gauge calibration.

Figure 3.11. - AARRP personnel downloading recorded rainfall data.

Figure 3.12. - Some AARRP staff at the Chiang Mai Royal Rainmaking Field Research Center.

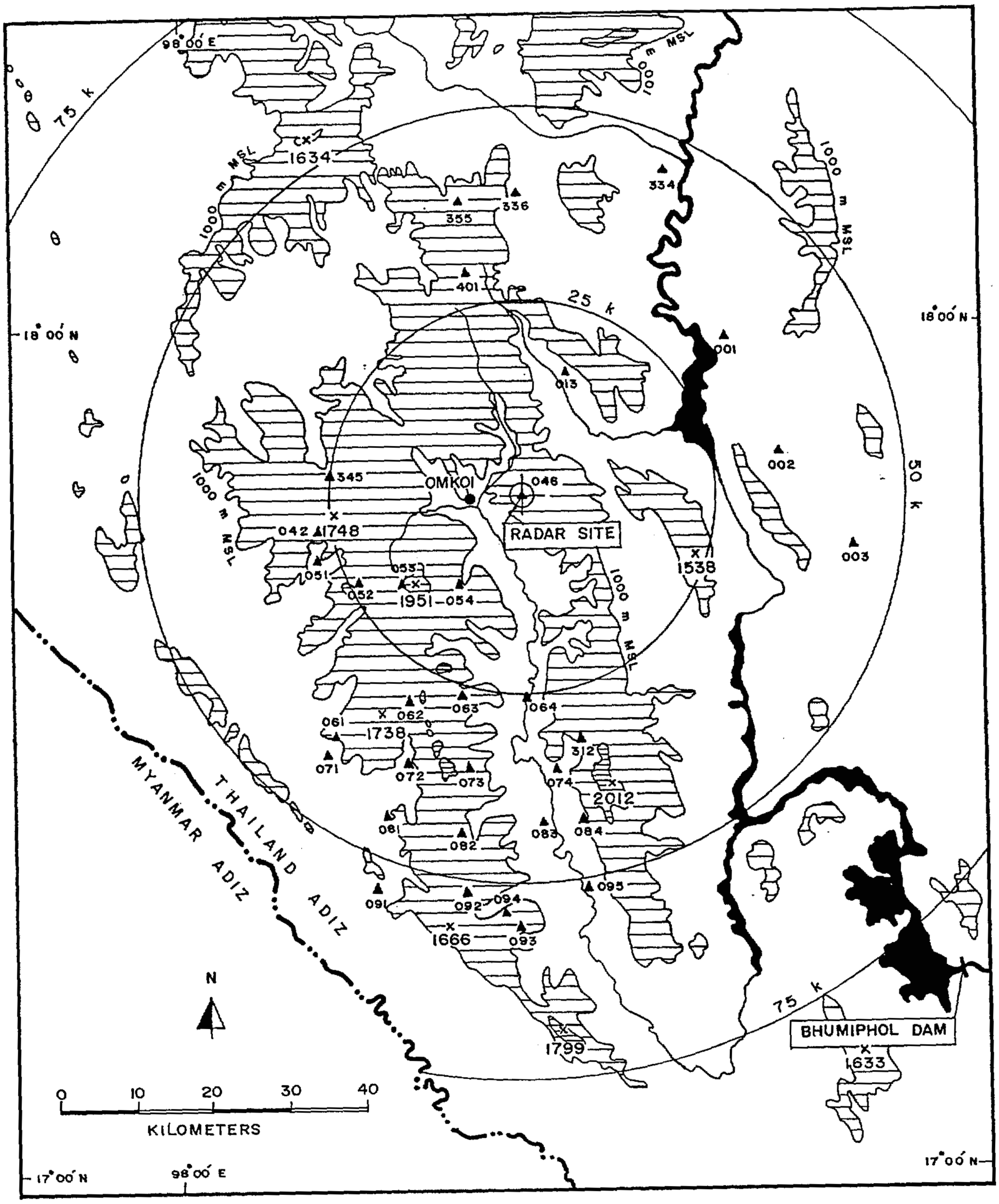

Figure 3.13. - AARRP project area showing radar site and Field Research Center.

4. CONTRIBUTIONS BY THE UNITED STATES GOVERNMENT

The goal of the AARRP, as revised by PASA Amendment 8, was stated in the **Introduction** section of this volume. Obtaining this program goal involved the provision of equipment and technical training, and the conduct of exploratory meteorological studies required for the development of the design and operations plan for Phase 2 of the AARRP, the demonstration project. The U.S. Government was responsible for achieving the program goal.

As a result of the U.S. Government's financial contributions, all approved equipment, including a Doppler weather radar system, an aircraft cloud physics DAS (data acquisition system), a network of recording rain gauges, a minicomputer, and various microcomputers with software, has been delivered and installed. U.S. Government experts have provided training on the operation and maintenance of this equipment. In addition, five Thai project personnel completed graduate training in meteorology at universities in the U.S., and in-country training was provided in basic radar technology, conducting scientific field research operations, data collection and processing, and data analyses required for the design of the demonstration project.

The total cumulative funding authorized in the USAID-Reclamation PASA through Amendment 11 was $3,804,300. Table 4.1 summarizes the budget line items as listed in the PASA and lists the cumulative cost for each budget item. Reclamation's work under the PASA was successfully completed on time and within budget.

Table 4.1. - Summary of PASA budget plan costs (PASA No. ANE-0337-P-IZ-8021-00).

Budget line item	Cost ($ x 10^3)
Reclamation managed funds	
Salaries (including leave)	864.5
Benefits	135.4
Space	59.4
Travel & per diem	174.1
Movement of effects/storage	15.2
Supplies & materials	18.3
Subcontracts	2,056.3
NASA GMS system (loan money)	150.0
Miscellaneous	49.4
Overhead	197.6
Subtotal Reclamation managed funds	3,720.2
USAID Mission direct	
In-country RSA support	84.1
Total funds obligated for PASA	3,804.3

The U.S. Government contributed a total of $4,581,300 to the AARRP. Of this amount, $4,077,900 was contributed by USAID; $84,100 in the PASA for USAID Mission in-country support of Dr. Silverman, the RSA, $423,600 in USAID Mission project support to the RTG, $3,570,200 in the PASA for Reclamation managed funds, and $161,000 in NASA contributed funds. This USAID contribution does not include the $150,000 in loan money for the GMS ingest and display system listed in table 4.1, which shows the PASA budget plan costs, because the RTG is to repay this loan. PASA Amendment 10 placed the $150,000 in loan money under Reclamation's control, and authorized Reclamation to procure and accept the satellite system on behalf of the RTG.

Reclamation transferred a surplus automatic tracking rawinsonde system to the USAID, who, in turn, donated the system to the AARRP. This system had a book value of $37,700.

NASA support for the AARRP was provided because of their interest in obtaining project radar and rainfall data for NASA's TRMM. NASA has a requirement to develop representative rainfall climatologies in the tropics in connection with the TRMM "ground truth" validation program. The Doppler weather radar and attendant rain gauges operated in connection with the AARRP are ideally suited and located for TRMM studies. NASA contributed $54,200 in equipment and supplies, and $85,000 for U.S. experts to provide training on rain gauge operations and basic radar theory. In addition, NASA provided $21,800 through an interagency agreement with Reclamation during the PASA suspension period, which allowed Mr. Curt Hartzell to make two trips to Thailand in support of both TRMM and the AARRP.

Details of the U.S. Government contributions made by USAID, Reclamation, and NASA are listed in table 4.2. The original PASA budget that was developed in FY-1988 included the following additional five budget categories under "Reclamation PASA Direct:"

- U.S. study tour
- Socioeconomic impacts
- Environmental impacts assistance
- Pilot agricultural drought warning study
- Analysis training

The budgets for these categories were subsequently reduced to zero, and the funds were transferred to items that were given a higher priority by the AARRP Steering Committee, based upon the recommendations of the RSA.

Table 4.2. - Summary of U.S. Government contributions to the AARRP.

Contribution item	Cost ($ x 10^3)
USAID Mission Direct	
In-country RSA support	84.1
USAID Mission Support to the RTG	
Long-term training abroad	250.0
Core training in-country	21.8
Research and study assistance	14.2
Quarterly review	30.0
Administrative support	107.6
Subtotal USAID Mission	507.7

Table 4.2. - Summary of U.S. Government contributions to the AARRP - continued.

Contribution item	Cost ($\$ \times 10^3$)
Reclamation PASA Direct	
Resident Scientific Advisor	265.6
Core training symposium	53.4
Scientific concept evaluation	30.7
Demonstration project design	38.7
Equipment specifications preparation	52.7
University training coordination	5.7
Scientific library upgrade	8.2
Software and training	61.6
Data management training	17.7
Scientific analysis assistance	370.0
Field operations assistance	455.3
Administrative support & reports	154.3
Subtotal Reclamation PASA Direct	1,513.9
Reclamation PASA Subcontracts	
Core training symposium	33.5
Scientific concept evaluation	26.3
Radar/rawinsonde technician training in USA	49.2
Doppler weather surveillance radar system	1,132.4
Aircraft cloud physics data acquisition system	207.9
Radio communications	45.9
Recording rain gauges	33.6
IRIS for MicroVax	63.4
Satellite remote workstation	51.5
Rawinsonde data processors	39.0
Microvax minicomputer system	157.9
Microcomputers and software	43.6
Global positioning systems for aircraft	20.0
Exploratory meteorological studies (WWC)	144.8
Shipping	7.3
Subtotal Reclamation Subcontracts	2,056.3
NASA Contributions	
Reclamation labor under Interagency Agreement	11.5
Reclamation travel under Interagency Agreement	10.3
Misc. supplies under Interagency Agreement	4.2
Training by U.S. experts in Thailand	85.0
Recording rain gauges and other supplies	36.0
Exabyte 8-mm tape recording systems	14.0
Subtotal NASA contributions	161.0
Total U.S. Government contributions	4,238.9

5. TECHNOLOGY TRANSFER

The areas of technology transfer for the AARRP included equipment operations and maintenance, dynamic cold cloud seeding principles and experimental studies, warm cloud seeding experimental studies, planning and conducting randomized field research experiments, data collection and processing, cloud modeling studies, scientific data analysis, and experimental evaluation. The transfer of technology to Thai project staff was accomplished through technical assistance provided by Reclamation experts and technical personnel, Reclamation PASA subcontractors, and NASA contractors.

5.1 Technical Assistance by Reclamation Personnel

Reclamation's technical team that worked on the AARRP, the labor effort for each team member, and the primary tasks performed by each team member, are listed in table 5.1. The tasks listed in table 5.1 were performed within the 12 PASA budget categories listed under the heading "Reclamation PASA Direct" in table 4.2. The total labor effort of 3155 days is comprised of 2876 days for the technical team members plus 279 days for nontechnical support. The technical team's labor effort included days during the period when the PASA was suspended, which were covered by NASA contributions. The cost for Reclamation salaries for all labor under the PASA is listed in table 4.1; Reclamation labor costs covered by NASA contributions are listed in table 4.2.

Table 5.1. - Reclamation's technical team for the AARRP.

Person	Days	Tasks
Dr. Bernard Silverman	1030	Project management and coordination, scientific planning, core training, resident scientific advisor, scientific data analysis and training, modeling, project design, and operations plan
Mr. Glenn Cascino	375	Equipment specifications, radar system and radio communications network installations, technical assistance, and training
Dr. Arnett Dennis	63	Administrative coordination
Mr. Dick Eddy	74	Administrative coordination
Mr. Curt Hartzell	724	Procurements, logistics, contract monitor, data processing and analysis, technical assistance and training, project operations plans
Mr. Matt Jones	16	MicroVax specifications
Dr. David Johnson	11	Scientific planning
Mr. John Lease	6	Administrative coordination
Mr. Jack McPartland	126	Aircraft instrumentation system
Mr. Jonnie Medina	127	Statistical design, core training seminar
Mr. Ron Miller	112	Computer program modifications
Dr. Roy Rasmussen	120	Scientific planning, core training seminar
Ms. Anne Reynolds	12	Software support
Mr. Dave Reynolds	28	Core training seminar
Mr. Mark Stieg	45	MicroVax systems management training
Dr. Arlin Super	7	Administrative coordination
Other nontechnical	279	Clerical, contracts, procurements, reports, etc.
Total days	3155	

Dr. Bernard Silverman was associated with the Thailand program from the time of the "Weather Modification Assessment" (Silverman et al., 1986) through the PASA ending date of March 31, 1994. However, the labor effort for Dr. Silverman listed in table 5.1 began in 1988 after the PASA was approved. During fiscal years 1989 and 1990, Dr. Silverman was stationed in Bangkok, where he served as the RSA for the AARRP. Other Reclamation personnel who put a significant effort into the AARRP were Messrs. Curt Hartzell and Glenn Cascino.

Reclamation's support for the AARRP required both international travel to Thailand and domestic travel within the United States by technical team members. The international and domestic travel by Reclamation personnel in conjunction with the AARRP is listed in tables 5.2 and 5.3, respectively. These tables list the traveler, a brief statement of the purpose for the travel, the travel dates, and the cost for the travel, per diem, and miscellaneous expenses. All Reclamation travel under the PASA was included in the PASA budget plan (original and amendments). Reclamation's travel costs under the PASA totaled $174,080 (compare with table 4.1). Additional travel to Thailand by Curt Hartzell during the PASA suspension period was funded by NASA contributions; the travel costs for these trips totaled $10,118.

Table 5.2 lists 35 trips covering 857 days; 33 trips were funded by the PASA, and 2 were funded by NASA contributions. The primary purpose for these trips was technology transfer. However, the tasks performed in Thailand by the Reclamation technical team included project planning and coordination, the monitoring of Reclamation subcontractors, assisting with the installation of equipment, on-the-job training, and formal training. The purpose for the 16 domestic trips (table 5.3) included coordination and planning with NASA, subcontractors, and Thai students/technicians at U.S. universities and subcontractor facilities; and equipment inspection and acceptance tests.

5.2 Technical Assistance by Reclamation Subcontractor Personnel

Reclamation subcontractors under the PASA made major technology transfer contributions to the AARRP. The PASA subcontracts and related costs are listed in table 4.2. The key areas where Reclamation subcontractors provided technical assistance for the AARRP under the PASA are listed in table 5.4. This table lists the subcontractor experts, their purpose or area of work and labor effort, and the travel days and periods for the experts who provided technical assistance in Thailand.

The first three items listed provided expertise for the core training in Thailand, scientific concepts and design evaluation assistance, and Thai engineer/technician training in the United States. The item listed as "Exploratory meteorological studies," was a contract with WWC (Woodley Weather Consultants) to provide the needed expert services for the transfer of dynamic cloud seeding and evaluation technology to Thailand, and implementing experimental studies for this cold cloud seeding technology as part of the AARRP.

The remaining items in table 5.4 were major equipment procurements for the AARRP. These PASA subcontracts included the shipping of the equipment to Thailand, installation of the equipment, and training on operations and maintenance. The costs listed in table 5.4 cover only the technical assistance provided by the experts; total costs are listed in table 4.2. Altogether, the subcontractor personnel made a total of 34 trips to Thailand over 752 days.

5.3 Technical Assistance by NASA Contractor Personnel

Technical assistance by non-Reclamation experts was provided for the AARRP by NASA in support of their TRMM ground truth validation program. The areas where this assistance was provided are listed in table 5.5 (compare with table 4.2). The format of the table is the same as table 5.4. The four NASA contractors listed made a total of eight trips to Thailand over 85 days; the total cost for this technology assistance was $85,000.

The NASA contributions were critical to the success of the AARRP. Mr. Ed Rich provided important technology transfer through the training of project personnel on tipping bucket rain gauge operations and maintenance, and then on downloading the collected data cartridges using a data translator and a personal computer. Drs. Paul Smith and Daniel Rosenfeld provided expert training on basic radar theory to RRRDI staff, to key members of the AARRP Technical Working Group, and to TMD staff. Mr. Tom Huang installed 8-millimeter tape recorders on the MicroVax systems located at RRRDI in Bangkok and the AARRP radar site near Omkoi for recording, copying, and reading radar data.

Table 5.2. - Reclamation's international travel in conjunction with the Thailand AARRP.

Traveler	Purpose	Travel Dates	No. Days	PASA Costs	Non-PASA Costs
Silverman	PCS move & other travel	9/88 - 9/90		$ 9103.81	
Cascino	Equipment specification preparation	1/8 - 1/30/88	23	5190.87	
Silverman	Core training seminar	1/29 - 2/14/88	16	2762.65	
Rasmussen	Core training seminar	2/15 - 2/28/88	14	3900.10	
Medina	Core training seminar	2/22 - 3/14/88	23	3973.37	
Reynolds	Core training seminar	1/22 - 3/13/88	22	3749.36	
Silverman	Core training seminar	3/3 - 3/20/88	18	2766.67	
Medina	Rain gauge network design	4/23 - 5/15/89	23	4479.15	
Hartzell	Technical assistance & training	5/10 - 6/11/90	32	6089.05	
Cascino	Equipment installation & training	5/16 - 6/3/90	18	3678.68	
Miller	Software installation & training	5/16 - 6/10/90	25	4691.80	
Hartzell	Technical assistance & training	9/17 - 10/11/90	25	5318.90	
Hartzell	NASA radar training course No. 1	12/3 - 12/23/90	21	4455.12	
Stieg	MicroVax system training	1/18 - 2/16/91	29	5883.90	
Silverman	Project oversight & planning	3/5 - 4/3/91	29	4691.25	
McPartland	Aircraft DAS contract monitor	4/5 - 5/10/91	36	4597.63	
Hartzell	Technical assistance & contract monitor	4/16 - 5/30/91	45	7999.13	
Stieg	MicroVax system training	4/22 - 5/10/91	19	3995.36	
Cascino	Radar system installation	5/16 - 6/25/91	40	5538.97	
Silverman	Scientific assistance & training	7/2 - 8/4/91	33	6132.05	
Hartzell	Data management training	8/6 - 9/12/91	37	5852.86	
Stieg	MicroVax system training	9/7 - 9/27/91	21	3939.29	
Cascino	Technical assistance - equipment	9/9 - 9/22/91	14	2645.49	
Silverman	Scientific assistance & planning	9/19 - 10/10/91	23	3836.40	
Hartzell	NASA radar training course No. 2	1/16 - 2/7/92	23		5340.86
Hartzell	Field operations assistance & TRMM	8/4 - 8/27/92	24		4977.04
Silverman	Scientific assistance & analysis	12/11/92 - 1/15/93	15	4927.43	
Hartzell	Technical assistance & analysis	1/15 - 1/29/93	15	5482.12	
Cascino	Technical assistance - equipment	3/15 - 4/10/93	27	5152.81	
Hartzell	Field operations assistance	3/18 - 4/19/93	33	5414.79	
Silverman	Scientific assistance & planning	4/2 - 4/25/93	24	3649.41	
Silverman	Scientific assistance & training	7/10 - 7/31/93	21	4647.03	
Hartzell	Field operations assistance	7/22 - 8/31/93	41	6788.83	
Silverman	Scientific analysis training	10/5 - 10/22/93	18	4573.83	
*Silverman	Phase 1 wrap-up meetings	2/21 - 3/7/94	15	4650.00	
*Hartzell	Phase 1 wrap-up meetings	2/21 - 3/7/94	15	4650.00	
Totals	35 trips		857	$165,208.11	$10,117.90

*Scheduled trips

Table 5.3. - Reclamation's domestic travel in conjunction with Thailand AARRP.

Traveler	Destination	Purpose	Travel Dates	No. Days	PASA Costs
Medina	Charlottesville VA	NASA coordination planning	1/8 - 1/11/89	4	766.14
Hartzell	Enterprise AL	EEC contract negotiations	7/16 - 7/17/90	2	632.00
Schlesier	Enterprise AL	EEC contract negotiations	7/16 - 7/17/90	2	595.08
Hartzell	Greenbelt MD	NASA coordination planning	7/24 - 7/26/90	3	625.82
McPartland	Erie CO	Aircraft DAS inspection	1/4 - 1/8/91	5	31.68
Hartzell	Enterprise AL	Radar technician training	1/7 - 1/10/91	4	1005.20
Hartzell	Ft. Collins CO	Rawin system transport	1/14/91	1	34.80
Cascino	Enterprise AL	Radar system inspection	2/18 - 2/22/91	5	911.17
Hartzell	Greenbelt MD	NASA satellite remote system	4/9 - 4/10/91	2	756.66
Silverman	Greenbelt MD	NASA coordination & planning	4/20 - 5/4/91	14	606.95
Silverman	Greenbelt MD	NASA coordination & planning	9/4 - 9/7/91	4	724.42
Hartzell	Ft Collins CO	Diplomatic assistance	9/26 - 10/2/91	7	207.60
Hartzell	Greenbelt MD	NASA coordination & planning	10/7 - 10/9/91	3	732.86
Silverman	Rapid City SD	University training coordination	10/22 - 10/23/91	2	285.71
Hartzell	Rapid City SD	University training coordination	10/22 - 10/23/91	2	210.69
Hartzell	Greenbelt MD	NASA GMS system inspection	7/19 - 7/21/93	3	745.15
Totals	16 trips			63	$8,871.93

Table 5.4. - Reclamation PASA subcontractor's technical assistance on equipment, operations, and training for the AARRP.

Expert	Purpose	Total Days	Travel Days	Travel Period
Core Training: Technical assistance costs $29,370				
Dr. G. Valie	Cloud seeding training	20	15	2/7-2/21/88
Dr. H. Orville	Cloud physics training	20	15	2/7-2/21/88
Scientific concepts evaluation: Technical assistance costs $26,313				
Dr. P. Mielke	Statistical design	5	none	n/a
Dr. R. Rasmussen	Cloud modeling study	4	none	n/a
GSA Tri-parts	Computer programming	120	none	n/a
Radar/rawinsonde technician training in USA: Technical assistance costs $25,962				
Paul Croft (EEC)	Doppler radar maint.	25	none	n/a
Don Cobb (ENSR)	Rawin system maint.	5	none	n/a
Doppler weather radar system: EEC installation and training costs $109,946				
Errol Messina	Radar site survey	10	7	9/30-10/6/90
Errol Messina	Radar system install.	40	30	5/13-6/11/91
Royce Morgan	Radar install. & train	45	35	6/3-7/7/91
Kurt Kleese	Radar IRIS training	15	15	7/5-7/19/91
Kurt Kleese	Refresher training	17	17	7/30-8/15/93
Aircraft cloud physics system: ASI installation and training costs $98,687				
Ed Neish	System install. & train	80	61	2/12/-4/13/91
Flip Pretorius	DAS install. & training	80	80	3/16-6/3/91
Bill Woodley	Operations training	55	47	4/18-6/3/91
Chip Taft	Pilot training	21	21	4/20-5/11/91
Flip Pretorius	DAS upgrade & training	20	20	7/12-7/31/91
Flip Pretorius	DAS upgrade & training	24	24	4/1-4/24/93
IRIS for MicroVax: Sigmet installation and training cost $14,400				
Tom Huang	Install. & training	25	15	5/18-6/1/91
Exploratory meteorological studies (WWC): Technical assistance costs $144,775				
Bill Woodley	Cold cloud studies	55	25	7/18-8/11/91
Danny Rosenfeld	Radar data analysis	45	27	7/16-8/11/91
Yoav Levy	Field ops. assist.	30	27	7/16-8/11/91
Bill Woodley	Cold cloud studies	20	19	9/23-10/11/91
Yoav Levy	Field ops. assist.	20	19	9/23-10/11/91
Bill Woodley	Cold cloud studies	95	56	4/13-6/7/93
Yoav Levy	Field ops. assist.	20	20	4/13-5/3/93
Eyal Amitai	Field ops. assist.	35	35	5/3-6/7/93
Danny Rosenfeld	Analysis software	65	11	10/4-10/15/93
Bill Woodley	Findings & ops. plan	20	14	2/21-3/6/94
Satellite remote workstation: NASA installation and training cost $10,000				
Gary McBrien	Install. & training	10	8	7/1-7/8/91
Paul Haggerty	Software training	10	5	7/4-7/8/91
Fran Stetina	System evaluation	5	2	9/21-9/22/91
NASA GMS Ingest and Display System: Installation and training costs $29,000				
Tom Moore	Site survey	10	7	7/1-7/7/93
Tom Moore	System installation	20	18	8/1-8/18/93
John Meredith	System installation	12	10	8/1-8/10/93
Peter Hill	Antenna system	8	5	8/14-8/19/93
Mike Comberiate	Project supervisor	20	13	8/14-8/26/93
Allen Lunsford	Install. & training	30	17	8/10-8/27/93
Gene Shafer	Install. & training	30	12	8/14-8/26/93
Totals: technical assist. costs $488,453		1191	752	34 trips to Thailand

Table 5.5. - NASA contribution of technical assistance on equipment, operations, and training for the AARRP.

Expert	Purpose	Total Days	Travel Days	Travel Period
Tipping bucket recording rain gauges: Technical assistance/training costs $30,000				
Ed Rich	Operations & maint.	15	10	5/13-5/22/90
Ed Rich	Operations & maint.	15	10	12/6-12/15/90
Ed Rich	Operations & maint.	15	10	4/24-5/3/91
First NASA sponsored radar course (December 11-20, 1990, Phuket): Cost $20,000				
Dr. P. Smith	Instructor	15	10	12/07-12/16/90
Dr. D. Rosenfeld	Instructor	15	10	12/12-12/21/90
Second NASA sponsored radar course (February 4-12, 1992, Phuket): Cost $20,000				
Dr. P. Smith	Instructor	15	12	2/2-2/13/92
Dr. D. Rosenfeld	Instructor	15	12	2/2-2/13/92
Exabyte 8-mm tape recorders: Sigmet installation and training cost $15,000				
Tom Huang	Install. & training	20	11	8/15-8/25/92
Totals: technical assist. costs $85,000		125	85	8 trips to Thailand

6. INSTITUTIONAL DEVELOPMENT

The new and final goal of the AARRP, as stated in the PASA, was quoted in the **Introduction** to this volume. Achieving this goal required the provision of equipment and training to carry out Phase 2 of the AARRP, namely, the follow-on demonstration project. Providing state-of-the-science equipment and training on the equipment, weather modification technology, and meteorology increased the capability of the BRRAA to fulfill its responsibilities for the AARRP. This "institutional development" of the BRRAA was one of the major objectives for the U.S. Government contributions.

6.1 Equipment Provided by the U.S. Government

The majority of the equipment provided to the RTG was purchased by Reclamation under the PASA and sent to Thailand for use on the AARRP. These purchases are included under "Reclamation PASA Subcontracts" in table 4.2; however, the costs listed include equipment installation and training (these costs were broken out in table 5.4). After the equipment items and/or systems had been installed, tested, and accepted by Reclamation, the equipment was transferred to the RRRDI, acting on behalf of the RTG. Table 6.1 is the log of all AARRP equipment transfer documents; this table provides a summary of the equipment transferred to the RTG under the PASA. The equipment transfers were comprehensive and included parts, supplies, and technical books, in addition to equipment hardware. Copies of these documents are on file at BRRAA. The one system listed in table 6.1 that was not purchased under the PASA was the Weathertronics rawinsonde receiving station (marked by *). This system was surplus Reclamation equipment that was transferred to USAID/Thailand, who, in turn, donated it to the RTG for use on the AARRP.

As stated previously, NASA also made equipment contributions for the AARRP in support of their TRMM ground truth validation program (see table 4.2 for costs). In particular, the network of remote recording rain gauges and the related rainfall data processing added significantly to the capability of the BRRAA. The items provided by NASA were:

- 50 Qualimetrics Model 6010 remote recording tipping bucket rain gauges.
- 11 Qualimetrics Model P100764 solid state event records for the rain gauges.
- 13 Qualimetrics Model 65351 data cartridges for the event recorders.
- 1 Qualimetrics Model 65353 data translator for downloading data from the data cartridges.
- 1 NASA assembled rain gauge maintenance kit.
- GEMS (Goldcrest Electronics Meteorological Software) for downloading and processing data.
- NASA manuals for rain gauge operations/maintenance and using GEMS.
- Miscellaneous spare parts for the tipping bucket rain gauges.
- 4 Exabyte 8-mm tape recorders with SCSI drive interface boards for MicroVax computers.
- Supply of 8-mm tapes for providing AARRP radar data to NASA (type example: Fuji P6-120).

The key equipment systems provided under the PASA for the AARRP that made major contributions toward the institutional development of the BRRAA were: (1) the Doppler weather surveillance radar system, (2) the aircraft cloud physics data acquisition system, (3) the MicroVax minicomputer system, and (4) the GMS ingest and display system. The GMS system was purchased by Reclamation under the PASA using USAID loan money; consequently, an equipment transfer document was not required, and this system was not included in table 6.1. These four equipment systems will be described in more detail in the following subsections.

Table 6.1. - Log of AARRP equipment transfer documents.

Document date	Brief description of equipment transferred to the RTG
July 31, 1989	Microcomputers and accessories, including one each of: Compaq Deskpro Model 20 computer Compaq dual mode monitor Compaq Deskpro 386S Model 40 computer NEC P5300 printer Automatic voltage regulator, Silicon Model SR-101
Aug. 9, 1989	30 technical books for RRRDI library upgrade and 20 computer software packages (listed in transfer document)
Aug. 17, 1989	Four additional technical books for RRRDI library (listed in transfer document)
Nov. 28, 1989	Computer hardware consisting of: Four NEC Multisync 3D VGA compatible monitors One NEC P5300 16-inch 24-pin dot matrix printer Three NEC P5200 9-inch 24-pin dot matrix printers
Feb. 20, 1990	Two Canon Model No. FAX-450 facsimile transceivers One Canon Model PC-7 plain paper copier
June 04, 1990	Various radio, rain gauge, computer equipment and accessories, and four technical books (listed in transfer document), including: Motorola: two HT600 hand held radios and three Maxtrac mobile radios Decibel Products: antennas General Electric: Master II base station with accessories Qualimetrics: event recorders, data cartridges, etc. for rain gauges Hewlett-Packard: HP 6-pen color plotter with supplies NEC: two Powermate 1 Plus, two Powermate 386/20 and one Powermate portable PC systems with accessories
Sept. 14, 1990	Electronic tools and supplies, and rain gauge parts (listed in transfer document)
Mar. 11, 1991	MicroVax 3400 minicomputer system
July 17, 1991	*Weathertronics RD65A rawinsonde receiving station
Sept. 10, 1991	One Chico Model No. EA800-01 recorder for rawinsonde system
Sept. 10, 1991	SPSS/PC+ V4.0 statistical software package for PCs
Sept. 10, 1991	EEC S-Band Doppler weather surveillance radar system
Sept. 10, 1991	IRIS analysis software with RGB 6-color display monitor for MicroVax 3400 system at RRRDI
Sept. 10, 1991	Additional hardware for MicroVax 3400 system (listed in transfer document)
Sept. 23, 1991	ASI DAS (Data Acquisition System), aircraft instrumentation, sensor calibration equipment, Trimble TNL-2000 GPS (global positioning system), Panasonic Model WV-CL110 video camera system, and Ikegami Model TVR-525 video recorder
Nov. 18, 1991	NASA remote meteorological satellite display system (listed in transfer document)
Nov. 18, 1991	Two Trimble Model No. TNL-2000 GPS
Nov. 18, 1991	Two Canon Model No. FAX-450 facsimile transceivers
Dec. 31, 1992	Computer hardware and software including; NEC Powermate 386/25 microcomputer system NEC Pinwriter 24-wire dot matrix printer NEC Multisync 2A color monitor Six software packages (listed in transfer document)

*Not purchased under the PASA; donated by Reclamation.

Table 6.1. - Log of AARRP equipment transfer documents - continued.

Document date	Brief description of equipment transferred to the RTG
Dec. 31, 1992	Microlab/FXR Model No. S638A S-Band Gain Horn for radar calibration
Dec. 31, 1992	Various radio equipment and parts, including two each of: 440-MHz RF Concepts Model 4-100 amplifier 12-V Astron Model RS-35M power supply Kantronics Data Engine with DE-1200 modem Kantronics DE-19K2/9K6 modem (installed in Data Engine) Kantronics D4-10 10-W Data Radio YAGI 12E antenna (10-dB gain / 40 degrees mainlobe width)
Dec. 31, 1992	AeroCommander 690B aircraft heat shield window covers Two radar Thyratron tubes, PN JAN 8613
Dec. 31, 1992	Various electronic equipment and tools (listed in transfer document), including: Jensen JTK-17LHST tool kit Tektronix Model 2235A portable oscilloscope Hewlett-Packard Model HP8683B signal generator Hewlett-Packard Model HP11582A attenuator set Hewlett-Packard Model HP432A power meter Hewlett-Packard Model HP478A thermistor mount EEC Model EEC-115653 Doppler test generator Microlab Model N410C frequency meter Fluke Model 8060A multimeter Two Weller Model WTCPSD soldering stations with accessories Hewlett-Packard Model HP7475A 6-pen color plotter
Dec. 31, 1992	Hewlett-Packard Model No. 478A thermistor mount (spare)
Jan. 4, 1993	S-COM Industries Model 6K radio repeater controller with telephone interface
Mar. 17, 1993	Panasonic Model AG-195P VHS record with case, Panasonic Model AG-W1-P video cassette player, BOGEN Model 3021 tripod, and ART 136 video head
Apr. 5, 1993	Philips 14-inch color monitor, Model No. 7CM3279/60T
Apr. 16, 1993	OCTOCOM Model OSI 8396 data modem
May 17, 1993	Two NEC 486 DX2/66e Model PM-910-2446 microcomputer systems Two AAMAZING Model CM-8486QX 14-inch VGA color monitors Three additional software packages (listed in transfer document)
May 17, 1993	Panasonic Model AG-195U VHS recorder replacement battery SIGMA 0.5X wide converter video lens for Panasonic VHS recorder
May 17, 1993	One GARMIN GPS100STD aircraft navigation system and two GARMIN GPS50 portable systems with mobile antennas
Aug. 15, 1993	One Tektronix PHASER II color printer for NASA remote satellite display system
Aug. 15, 1993	One Garmin GPS100STD aircraft navigation system.
Aug. 15, 1993	One EEC radar video processor, RVP-5 PCA, and one EEC radar control processor, EEC-123443 PCA
Jan. 25, 1994	Two RF72E-SF units, installed on the MicroVax at RRRDI to provide additional hard disk storage
Mar. 11, 1994	One Hewlett-Packard Model 4L Laser Jet Printer
Mar. 31, 1994	One Ultralite Model PC-410-0511 Versa Modular Notebook Computer system, plus four additional software packages (listed in transfer document)

6.1.1 Doppler weather surveillance radar system

The Doppler weather surveillance radar system was the largest procurement made by Reclamation under the PASA for the AARRP. The subcontractor for this system was EEC (Enterprise Electronics Corporation), who manufactured the system, shipped it to Thailand, and supervised the installation of the system at the AARRP radar site constructed by the RTG near Omkoi (site appears on figs. 3.4 and 3.5).

The model DWSR-88S radar system provided by EEC was completely solid-state technology, except for the magnetron, TR (transmitter-receiver) tube, thyratron, and CRTs (cathode-ray tubes), which provide the highest reliability and performance. The principal radar system characteristics are as follows:

· Frequency	2.7 to 2.9 GHz
· Wavelength	10.8 cm (S-band)
· Peak transmitted power	500 kW
· Pulse duration (width)	2.0 µs for intensity mode (reflectivity) 0.8 µs for velocity mode
· PRF (Pulse repetition frequency)	250 pulses/s for intensity mode Dual 600 to 1000 pulses/s for velocity mode
· MDS (Minimum detectable signal)	-106 dBm
· Antenna diameter	6.1 m (beam width about 1.2°)

The data acquisition and products processing CPU (central processing unit) for the radar system is a DEC (Digital Equipment Company) MicroVax 3400 minicomputer. The system software includes the IRIS/VMS radar analysis software package, developed by Sigmet, Inc. Digital data are recorded by a TK-70 296-megabyte cartridge tape recorder and an Exabyte 8-millimeter 2.4-gigabyte cassette tape recorder (provided by NASA). A remote color graphics display unit was provided that allows radar images to be remotely displayed at the AARRP Field Operations Center in Chiang Mai.

This DWSR-88S radar system was installed, tested, calibrated, and accepted during the May-July 1991 period. The installation work was supervised by EEC experts Errol Messina and Royce Morgan. Much of the work was performed by Thai project personnel, who were supervised by Khun Noppadol Boonyachalito. Reclamation technical team members Curt Hartzell and Glenn Cascino were on-site to assist with the installation, monitor the EEC contract work, participate in the system tests, and accept the system for the AARRP.

6.1.2 Aircraft cloud physics data acquisition system

An aircraft cloud physics data acquisition system was purchased for the AARRP under the PASA through a contract issued by Reclamation to ASI (Aero Systems, Inc.). The contract included fabrication of the instrumentation system and installation of the complete system in an AeroCommander 690B aircraft (shown on fig. 3.3) leased by the RTG. The key components of the system are as follows:

- Cloud Technology JW liquid water content sensing system (heated).
- General Eastern Corporation Hygrometer, model 1011B, for dew/frost point temperature.
- Minco/Temptan reverse flow temperature sensor, model TT110TDIM.

- Ball variometer, model M-50, with serial output and 2000-ft/s face, for rate of climb.
- Validyne P-24A absolute pressure transducer (altitude data).
- Validyne P-24D differential pressure transducer (true airspeed).
- Aero Instruments PH502 heated pitot tube to provide pressure inputs to the absolute and differential pressure transducers.
- Two Aero Instruments ST300 static buttons to provide static pressure input to the differential pressure transducer.
- Trimble GPS, model TNL-2000.
- DAS (Data acquisition system, including a NEC 386/25 Powermate microcomputer system and a Keithley A to D converter.
- Floating pointer system allowing return to selected convective cloud.
- Panasonic camera system and Ikegami time lapse VHS video recorder for cloud photography.

ASI installed the system at the Thai Agricultural Aviation Service's facility in Nakhon Sawan, Thailand, during the March-May 1991 period. The installation work was performed by ASI experts Ed Neish and Flip Pretorius. Reclamation technical team member Jack McPartland monitored the contract work and participated in the system tests in Thailand. After the system was demonstrated to perform at contract specifications, Mr. McPartland accepted it for the AARRP. DAS upgrades were subsequently accomplished by Flip Pretorius in July 1991 and April 1993. The Thai technical team that assisted with the installation work and tests was headed by Khun Warawoot Ninwiboon.

6.1.3 MicroVax minicomputer system

Reclamation purchased a DEC MicroVax 3400 minicomputer system under the PASA from Digital Equipment (Thailand) LTD for the AARRP. This MicroVax 3400 system was installed at the BRRAA (then RRRDI) in Bangkok by DEC Thailand technicians during December 1990. The system specifications as listed in the contract are listed by DEC part and model numbers; consequently, they would be of little use to the reader if listed here. However, the specifications are listed in detail in the equipment transfer document, a copy of which is on file at the BRRAA.

Reclamation MicroVax expert, Mark Stieg, inspected the installation and operation of the MicroVax 3400 system at the BRRAA during February 1991. He confirmed that everything ordered under the contract with DEC Thailand had been delivered and was working. The Thai project staff member who worked with Mark Stieg on the MicroVax system was Khun Rachaneewan Talumassawatdi. Additional hard disk storage was subsequently added by Reclamation under the PASA by a 1993 purchase order with DEC Thailand. This additional hard disk storage capability was needed for the analysis of project radar data, using software provided by Dr. Daniel Rosenfeld under a Reclamation contract with Woodley Weather Consultants.

6.1.4 GMS ingest and display system

PASA Amendment 10 authorized Reclamation to procure and accept a NASA 3400M GMS system for the AARRP on behalf of the Thai Ministry of Agriculture and Cooperatives. This system was procured through an interagency agreement between NASA's International Data Systems Office and Reclamation. The NASA 3400M GMS ingest and display system was designed to automatically receive and display GMS IR (infrared) and VIS (visual) data. The system consists of an antenna/front-end, ingest and processing computer, display computer, and all necessary software for the hands-off ingest and processing of GMS data. The principal components of the NASA 3400M GMS system provided for the Thailand AARRP are:

- Prodelin 3.8-m offset feed prime focus parabola antenna.
- LNA (Little Noise Amplifier)/DC (Downconverter).
- GMS S-VISSR Receiver/DC (second DC, BPSK demodulator, data bit synchronizer).
- Frame formatter (formats, blocks, and writes data to disk file).
- DEC MicroVax 3400 processing computer subsystem.
- Macintosh II display computer workstation.
- DECNET LAN (local area network).
- TK70, 4-mm and 8-mm tape drives.
- Uninterruptible power supply.

Reclamation technical team member Curt Hartzell participated in the GMS system tests at NASA/Goddard Space Flight Center during July 1993. Following his acceptance of the GMS system, it was shipped by NASA to Thailand, and installed at the AARRP radar site near Omkoi during August 1993. The NASA team that installed this system is listed at the end of table 5.4. Reclamation's representative, Curt Hartzell, was in Thailand during the installation period to coordinate the effort with AARRP management. The Thai engineer team, headed by Khun Warawoot Ninwiboon, and other project personnel stationed at the radar site, assisted with the installation of the system.

After the NASA 3400M GMS system was operational, the NASA team was able to connect the system to the NASA satellite remote workstation that had been procured previously under the PASA for the AARRP. This workstation was initially brought to the AARRP radar site for tests; the remote display workstation worked properly when the two systems were located next to each other. The satellite remote workstation was then transported to the AARRP's Field Operations Center in Chiang Mai and connected to the new NASA system at the radar site by data modems and a dedicated telephone line. The Thai engineer team and AARRP Field Operations Director, Khun Wathana Sukarnjanaset, were subsequently successful in making the workstation operational at the Field Operations Center.

6.2 Training Provided by the U.S. Government

Scientific and technical training to improve the knowledge and capability of BRRAA staff was one of the key objectives to be accomplished under the PASA. This training was provided through (1) a core training symposium, (2) long-term training at universities in the U.S., (3) short-term technical training in the U.S., and (4) short-term training courses given in Thailand. These four areas of training will be discussed in more detail in the following subsections.

6.2.1 Core training symposium

The core training symposium was held in Chiang Mai, Thailand, over the 5-week period from February 9 to March 11, 1988. Although the USAID/Reclamation PASA was not signed until April 8, 1988, a preincurred cost clause in the PASA allowed this symposium to be held prior to the rainy season in Thailand, so as not to interfere with existing BRRAA warm cloud seeding operations.

The purpose for this course was to provide core training in theoretical and applied cloud physics and weather modification for Thai personnel. The training course was officially named the Atmospheric Water Resources Management Symposium.

Details on the Atmospheric Water Resources Management Symposium are contained in Reclamation's interim scientific report "Applied Atmospheric Resources Research Program in Thailand" (Medina et al., 1989), and will not be repeated here. The lectures at the symposium were given by the following six U.S. experts on cloud physics, weather modification, and field research programs:

- Dr. Bernard A. Silverman (geophysical sciences) - Reclamation
- Dr. Gabor Vali (physics) - University of Wyoming
- Dr. Harold D. Orville (meteorology) - South Dakota School of Mines & Technology
- Dr. Roy M. Rasmussen (atmospheric sciences) - Reclamation
- Mr. Jonnie G. Medina (statistical meteorology) - Reclamation
- Mr. David W. Reynolds (atmospheric sciences) - Reclamation

There were 41 persons from Thailand that registered for the symposium. In addition to PASA funds for Reclamation to put on this symposium, the USAID Mission provided additional funds to the RTG to support core training participation by Thai officials (see table 4.2).

6.2.2 Long-term training at universities in the U.S.

The long-term training program was very important for the institutional development of the BRRAA. Funding support for this training covering tuition, books, subsistence, and other related costs, was provided by the USAID Mission to the RTG (see table 4.2). The RTG contributed the airfares and continued salary support. In 1989, five BRRAA staff members were selected for 2-year programs leading to master of science degrees in meteorology at U.S. universities. Two of the individuals selected, Khun Warawut Khantiyanan and Khun Wathana Sukarnjanaset, were enrolled in the Department of Meteorology at the South Dakota School of Mines & Technology; the other three, Khun Kiattisak Thangtrongsakol, Prinya Sudhikoses, and Maneewan Tisara, were enrolled in the Department of Meteorology at the University of Hawaii at Manoa. All five began their long-term training in early January 1990.

Table 6.2 provides a summary of the long-term training. The first three students listed in table 6.2 were able to complete the master of science degree requirements within the 2-year program time limit. As can be seen from the thesis titles, their training program areas were focused on AARRP needs. The two students who were not awarded degrees still benefitted greatly from the training. Following their return to the BRRAA, Khun Warawut, Wathana, and Prinya were assigned to key leadership positions for the AARRP (see fig. 2.2). Khun Kiattisak and Maneewan were assigned to other BRRAA program positions.

6.2.3 Short-term technical training in the U.S.

In 1990, after Reclamation entered into a contract with EEC for the Doppler weather surveillance radar system, arrangements were made to bring five individuals to the U.S. under the PASA for training on this radar system at EEC, during the period when the system was being assembled and tested. Because the TMD had recently installed a similar radar system at Phuket, Thailand, and because of the desire to support cooperation between the BRRAA and the TMD, two of the training positions were reserved for TMD electronics engineers.

Table 6.3 provides a summary of this short-term technical training. In early 1991, the following five Thai engineers and technicians came to the U.S. under the PASA for a 6-week (including travel) radar and rawinsonde system training program:

- Khun Noppadol Boonyachalito (electronics engineer) - BRRAA
- Khun Warawoot Ninwiboon (electronics technician) - BRRAA
- Khun Kamol Siriburanapanont (radar technician) - BRRAA
- Khun Charoen Chootirak (electronics engineer) - TMD
- Khun Supak Dang-Intawat (electronics engineer) - TMD

Table 6.2. - Summary of long-term training at universities in the U.S.

Name	Start date	End date	Months	Training area
Department of Meteorology, South Dakota School of Mines & Technology				
Warawut Khantiyanan	Jan. 1990	Jan. 1992	24	Cloud physics Master of science in meteorology Thesis: A comparative study of 1986 COHMEX radar and rain gage estimates of rainfall.
Wathana Sukarnjanaset	Jan. 1990	Jan. 1992	24	Cloud physics Master of science in meteorology Thesis: Numerical simulation of South African cumulus clouds.
Department of Meteorology, University of Hawaii at Manoa				
Kiattisak Thangtrongsakol	Jan. 1990	Jan. 1992	24	Tropical meteorology Master of science in meteorology Thesis: Analysis of an upper-level cold low during the early summer season over East Asia.
Prinya Sudhikoses	Jan. 1990	Jan. 1992	24	Hydro/Agrometeorology Graduate studies in meteorology
Maneewan Tisara	Jan. 1990	Feb. 1991	13	Tropical meteorology/general Graduate studies in meteorology

Table 6.3. - Summary of short-term technical training in the U.S.

Training area	Location	Days	Instructor
DWSR-88S Doppler weather radar (system configuration and maintenance)	EEC, Enterprise, AL	25	Paul Croft
RD65A rawinsonde system (installation, maintenance, and operation)	ENSR, Ft. Collins, CO	3	Don Cobb
Rawinsonde data processing (using Reclamation developed software)	Reclamation, Denver, CO	2	Curt Hartzell

6.2.4 Short-term training courses given in Thailand

In addition to the on-the-job type training provided during the technical assistance discussed in the **Technology Transfer** section of this volume, Reclamation experts, Reclamation PASA subcontractors (see table 5.4), and NASA contractors (see table 5.5) gave more formal short training courses to provide new knowledge and capabilities for BRRAA staff. Table 6.4 provides a summary of this training.

Table 6.4. - Summary of short-term training courses given in Thailand.

Training area	Date/location	Days	Instructor
Training courses given by Reclamation technical team experts			
Basics of FORTRAN code and programming	Jan. 1990/BRRAA	5	Dr. Silverman
MicroVax systems management	Feb. 1991/BRRAA	2	Mark Stieg
HAMOD convective cloud model (theory, limitations, and applications)	May 1991/BRRAA	3	Dr. Silverman
AARRP data management (inventory, quality control, and archiving)	Aug. 1991/BRRAA	2	Curt Hartzell
Randomized seeding design studies (Monte Carlo crossover simulations)	Jan. 1993/BRRAA	2	Dr. Silverman
Processing of AARRP rainfall data (quality control, file editing, analysis)	Mar. 1993/Chiang Mai	2	Curt Hartzell
Use of radar data PDF files in analysis (Probability density functions (PDF) - see Rosenfeld)	Oct. 1993/BRRAA	2	Dr. Silverman
Training courses given by Reclamation PASA subcontractors			
MicroVax 3400 system manager course	Jan. 1991/BRRAA	5	DEC Thailand staff (contract)
MicroVax 3400 utilities and command course	Jan. 1991/BRRAA	5	DEC Thailand staff (contract)
Aircraft cloud physics DAS (components and principles of operation)	Feb. 1991/BRRAA	5	Ed Neish (ASI contract)
Aircraft cloud physics DAS (installation, calibration, and maintenance)	Mar. 1991/Nakhon Sawan	10	Ed Neish (ASI contract)
Aircraft cloud physics DAS (system operations and data processing)	Apr. 1991/Nakhon Sawan	10	Flip Pretorius (ASI contract)
AeroCommander 690B pilot training (aircraft checkout and cloud penetrations)	Apr. 1991/Nakhon Sawan	5	Chip Taft (ASI contract)

Table 6.4. - Summary of short-term training courses given in Thailand - continued.

Training area	Date/location	Days	Instructor
Training courses given by Reclamation PASA subcontractors - continued			
Dynamic cold cloud seeding (concepts and experimental studies)	May 1991/Bhumibol Dam	10	Dr. Woodley (ASI contract)
IRIS (use of IRIS radar data analysis on MicroVax)	May 1991/BRRAA	7	Tom Huang (Sigmet contract)
DWSR-88S Doppler radar system (calibration, maintenance, and operation)	June 1991/Omkoi site	10	Royce Morgan (EEC contract)
DWSR-88S Doppler radar system (system operations and IRIS applications)	July 1991/Omkoi site	10	Kurt Kleese (EEC contract)
Remote satellite workstation (use of workstation and software)	July 1991/Bhumibol Dam	2	Paul Haggerty (NASA contract)
Cold cloud seeding experimental studies (operations plan and data processing)	Aug. 1991/Bhumibol Dam	5	Dr. Woodley (WWC contract)
Cold cloud seeding experimental studies (procedures, data processing and evaluation)	May 1993/Chiang Mai	10	Dr. Woodley (WWC contract)
Aircraft cloud physics DAS refresher training (maintenance, calibration, operations, data processing)	Apr. 1993/Chiang Mai	5	Flip Pretorius (ASI contract)
DWSR-88S radar system refresher training (troubleshooting, calibration, IRIS)	Aug. 1993/Omkoi site	10	Kurt Kleese (EEC contract)
NASA GMS 3400M ingest and display system (antenna/front end alignment and maintenance)	Aug. 1993/Omkoi site	2	Peter Hill (NASA contract)
NASA GMS 3400M ingest and display system (configuration, maintenance, and operation)	Aug. 1993/Omkoi site	4	Allen Lunsford (NASA contract)
NASA GMS 3400M ingest and display system (software applications and data interpretation)	Aug. 1993/Omkoi site	4	Gene Shafer (NASA contract)
Processing and analysis of radar data (creating probability density functions)	Oct. 1993/BRRAA	8	Dr. Rosenfeld (WWC contract)

Table 6.4. - Summary of short-term training courses given in Thailand - continued.

Training area	Date/location	Days	Instructor
<u>Training courses given by NASA contractors</u>			
Tipping bucket recording rain gauge system (components and principles of operation)	May 1990/BRRAA	1	Ed Rich
Recording rain gauge setup procedures (calibration, installation, and servicing)	May 1990/Chiang Mai	2	Ed Rich
Recording rain gauge operations (review of gauge servicing and maintenance)	Dec. 1990/Phuket	2	Ed Rich
NASA introductory radar course No. 1 (weather radar fundamentals and applications)	Dec. 1990/Phuket	5 3	Dr. Smith Dr. Rosenfeld
Recording rain gauge data processing (refresher training on GEMS software)	Apr. 1991/Chiang Mai	2	Ed Rich
NASA introductory radar course No. 2 (radar theory, calibration, and applications)	Feb. 1992/Phuket	4 4	Dr. Smith Dr. Rosenfeld
Recording/copying radar data on 8-mm tapes (use of Exabyte 8-mm tape drives on MicroVaxs)	Aug. 1992/BRRAA	1	Tom Huang

7. SCIENTIFIC ACCOMPLISHMENTS

The AARRP produced many scientific accomplishments. Detailed accounts of these scientific accomplishments are presented in "Volume 2 - Demonstration Project Design." In this section, some of the key scientific accomplishments are summarized in three categories: general, cold cloud, and warm cloud.

7.1 General Accomplishments

The key findings of a general nature are:

1. Thai scientists improved and, in some cases, first developed skills in the operation and scientific application of powerful microcomputers and a minicomputer provided through the AARRP.

2. Thai scientists, engineers, and technicians achieved a greatly improved capability to organize, implement, and direct scientific field experiments involving multiple and complex measurement systems focused on achieving sophisticated scientific objectives.

3. Numerical cloud modeling studies indicate that the CCN (cloud condensation nucleus) spectrum upon which warm and cold clouds develop in the project area has a strong influence on the production of natural rainfall from these clouds. As the CCN spectrum changes from one primarily maritime in character (low number concentration and relatively high numbers in large nuclei sizes) to one that is more continental in character (high number concentration and very few in large nuclei sizes), the amount of natural rain produced decreases markedly. The decrease is greater in warm clouds which depend solely on the condensation-coalescence process for precipitation development than in cold clouds, which include precipitation development through ice processes as well. The burning of rice fields and forest areas in the project area produces a smoke containing nuclei which, from evidence in other projects, suggests that the natural CCN spectrum is probably being made more continental in character.

4. A greatly improved understanding of the frequency of warm and cold seeding opportunities was achieved.

5. A preliminary objective technique for forecasting convective cloud-top heights in the AARRP project study area was developed. The technique is based on a simple, real-time computer analysis of the Chiang Mai 0000 GMT (Greenwich mean time) (0700 LST) upper-air sounding. Statistical correlation and regression analyses compared the sounding-based predictions with the 95-percentile radar echo tops observed during the 6-hour afternoon period over the target area. The results from the study show that this objective technique provides useful operational guidance, but needs further development before being used to prestratify the days for randomized warm and cold cloud seeding operations.

6. An improved understanding of the hydrometeorology of northern Thailand was achieved. At the time that the Thailand Weather Modification Assessment was conducted in September 1986, both the storage and reservoir level in the Sirikit reservoir system were above normal by about 6 percent and 15 percent, respectively.

In the Bhumibol reservoir system, the reservoir level was approximately normal and the storage was 11 percent above normal. The mean annual rainfall in the Bhumibol and Sirikit catchment areas was higher prior to commissioning of the Bhumibol and Sirikit dams than afterwards. Both the Bhumibol and Sirikit reached their all-time low values in June 1992; both the Bhumibol and Sirikit were critically close to their respective drawdown levels (see fig. 7.1). Of greatest significance was the finding that the percentage of rain falling in the catchment areas that reached the reservoir has steadily decreased since about 1984 for the Bhumibol reservoir system and about 1985 for the Sirikit reservoir system.

7.2 Cold Cloud Accomplishments

7.2.1 Results of field studies

The cold cloud field studies resulted in the following key findings:

1. Thai supercooled clouds are highly suitable for dynamic, cold cloud seeding intervention, especially those with low warm cloud bases having an active coalescence process.

2. Clouds suitable for cold cloud seeding are most frequent over the project area during the pre- and post-monsoon periods; a typical example is shown on figure 7.2. During the monsoon season, suitable convective clouds over the project area occur less frequently; they occur more frequently primarily to the northeast, east, and southeast of the project area beyond quantitative radar range.

3. Pre-monsoon convective clouds often have higher and cooler cloud bases than those that form during the monsoon period. In addition, droplet coalescence with the pre-monsoon clouds appears to be less active than in the monsoon clouds.

4. The smoke produced by the burning of the rice fields during the pre-monsoon period was observed to inhibit cloud and precipitation development in those areas affected by the smoke plume.

7.2.2 Results of experimental seeding

The cold cloud seeding experiments resulted in the following key findings:

1. The randomized cold cloud seeding experiments were executed exceptionally well and resulted in the qualification of 14 experimental units in 1993.

2. For this small sample, seven seed and seven no-seed cases, the seeded clouds produced more rainfall than the nonseeded clouds. The largest visual cloud response to seeding occurred in clouds with relatively warm cloud base temperatures. These findings are consistent with results of similar cold cloud seeding experiments in Florida and Texas in the U.S.

3. A total of 151 convective cells, 87 seeded and 64 nonseeded, were identified within the experimental units and their properties computed through analysis of the AARRP radar data. The results suggest that the AgI seeding increased the maximum cell

areas by 25 percent, cell durations by 14 percent, and rain cell volumes by 69 percent. Little effect is indicated for maximum cell heights. Results for the sample with cloud base temperatures warmer than 16 °C suggest a seeding effect of 71 percent, 33 percent, and 125 percent for cell areas, cell durations, and rain cell volumes, respectively. The increase in maximum cell height was about 6 percent.

4. Within the height range of 7 to 11 kilometers, seeded cells of a given maximum radar echo top height produced more rain than nonseeded cells of the same height.

5. None of the above results have strong statistical support because of the small sample and high sample variances; however, the results strongly support the conduct of a follow-on cold cloud seeding demonstration project to quantify with statistical confidence the amount of additional rainfall that could be produced as a result of dynamic, cold cloud seeding.

6. Calculations indicate that the sign and magnitude of a cold cloud seeding effect could be established at a significance level of 5 percent and power of detection of 90 percent with a sample size that could be obtained within 5 years, provided that the future frequency of seeding opportunities is consistent with that of the past and that most, if not all, of these occurrences are successfully treated.

7.3 Warm Cloud Accomplishments

7.3.1 Results of numerical model seeding experiments

The numerical model warm cloud seeding experiments resulted in the following key findings:

1. Hygroscopic seeding is effective in increasing precipitation from both warm and cold clouds. An example of warm convective clouds is shown on figure 7.3.

2. Hygroscopic particle seeding leads to increased precipitation by producing microphysical effects that improve the precipitation efficiency of warm and cold convective clouds. No dynamic effects occur as a result of the exothermic or endothermic nature of the hygroscopic chemicals.

3. Of the various hygroscopic chemicals used for warm cloud seeding in Thailand, $CaCl_2$ is the most effective.

4. Hygroscopic particle seeding effectiveness depends most strongly on particle size. Depending on the seeding strategy, particle sizes less than or equal to 50 micrometers radius are most effective. Seeding with polydisperse $CaCl_2$ spectra as obtained from the chemical supplier produces meaningful and measurable increases in rainfall, although not as much as could be achieved with idealized monodisperse spectra.

5. Hygroscopic particle seeding at cloud base produces more rainfall than seeding near cloud top; however, both produce significant increases in rainfall.

6. The effectiveness of hygroscopic particle seeding depends strongly on the time of seeding, and is only effective when seeding is performed early in the life of the growing cloud when precipitation initiation and development processes can still be influenced.

7. The percentage increase in rain caused by hygroscopic particle seeding of warm clouds decreases with increasing natural cloud rain efficiency and rain production. Clouds that would not otherwise rain can be induced to rain by hygroscopic particle seeding. The percentage increase in rainfall in relatively efficient natural clouds is significant and, measured on an absolute basis, is greater than the increase from less efficient natural clouds. Similar relationships are indicated for hygroscopic particle seeding of cold clouds, but they are less dramatic because of the additional involvement of ice processes in the rainfall evolution processes.

8. Hygroscopic flare seeding in the subcloud layer prior to cloud formation can increase the rainfall of clouds that eventually develop on the modified CCN spectrum. The effectiveness of the hygroscopic flare seeding depends strongly on the natural CCN spectra of the area, being more effective in cases where the natural CCN spectra is more continental in character.

9. Hygroscopic seeding experiments with $CaCl_2$ particles and hygroscopic flares were conducted on warm and cold clouds with CCN spectra varying from maritime to continental, and the results were normalized against the natural rainfall from the cloud with the most maritime CCN spectra [referred to as the MNR (maximum natural rainfall)]. This experimentation was done to see if and by how much seeding can restore the rainfall from clouds with the more continental CCN spectra to the value obtained with a relatively pristine maritime CCN spectrum. The $CaCl_2$ seeding of the cold clouds does, in fact, result in the production of more rain than the MNR in all cases. For the warm clouds, $CaCl_2$ seeding never results in more rain than the MNR, even though the seed/no-seed ratios are substantially greater than one. Flare seeding, on the other hand, never results in more rain than the MNR for the cold clouds, and only exceeds the MNR for warm clouds for the cases in which the flare seeding modifies the natural CCN spectra to produce a lower CCN concentration than the no-seed MNR case.

10. The results of the numerical model hygroscopic particle seeding experiments strongly support the conduct of a warm cloud seeding demonstration project to quantify with statistical confidence the amount of additional rainfall that could be produced as a result of static, warm cloud seeding.

11. Calculations indicate that the sign and magnitude of a warm cloud seeding effect could be established at a significance level of 5 percent and power of detection of 90 percent with a sample size that could be obtained within 5 years, provided that the future frequency of seeding opportunities is consistent with that of the past and that most of these occurrences are successfully treated.

7.3.2 Results of field activities

The warm cloud seeding trials resulted in the following key accomplishments:

1. Thai scientists gained valuable experience in the qualification of warm cloud experimental units.

2. A viable seeding strategy for executing the warm cloud seeding operation with two seeding aircraft and the AeroCommander observation aircraft in a safe and effective manner was developed and practiced.

3. Two pairs of well correlated target areas were identified that are suitable for conducting warm cloud seeding in the morning and afternoon hours in accordance with a randomized crossover design.

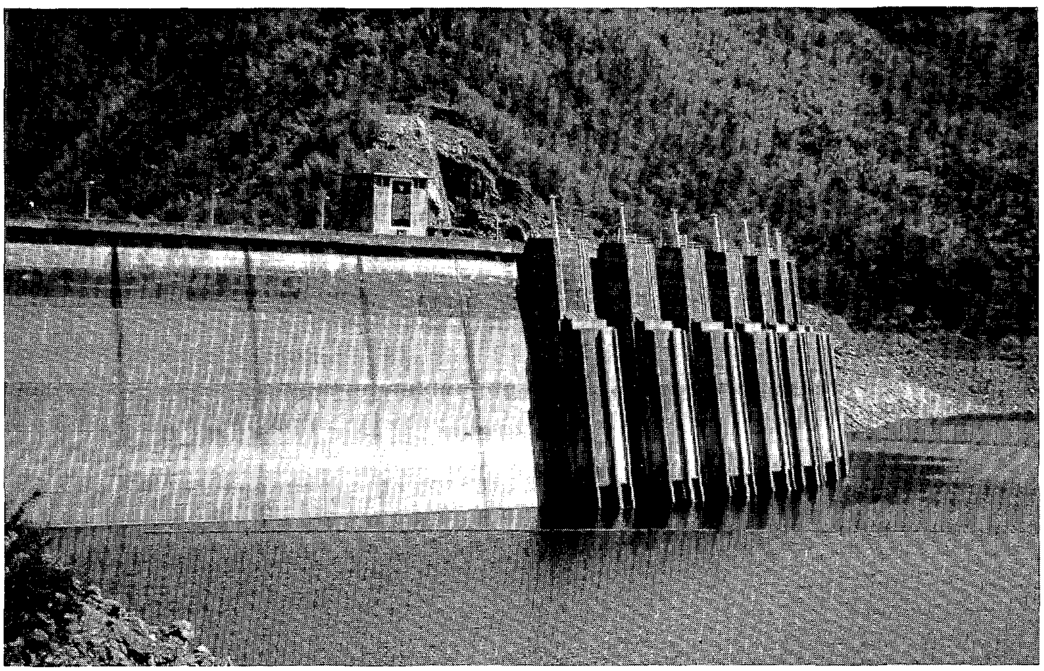

Figure 7.1. - Bhumibol Dam showing low reservoir level.

Figure 7.2. - Example of cold convective clouds over Tak, Thailand.

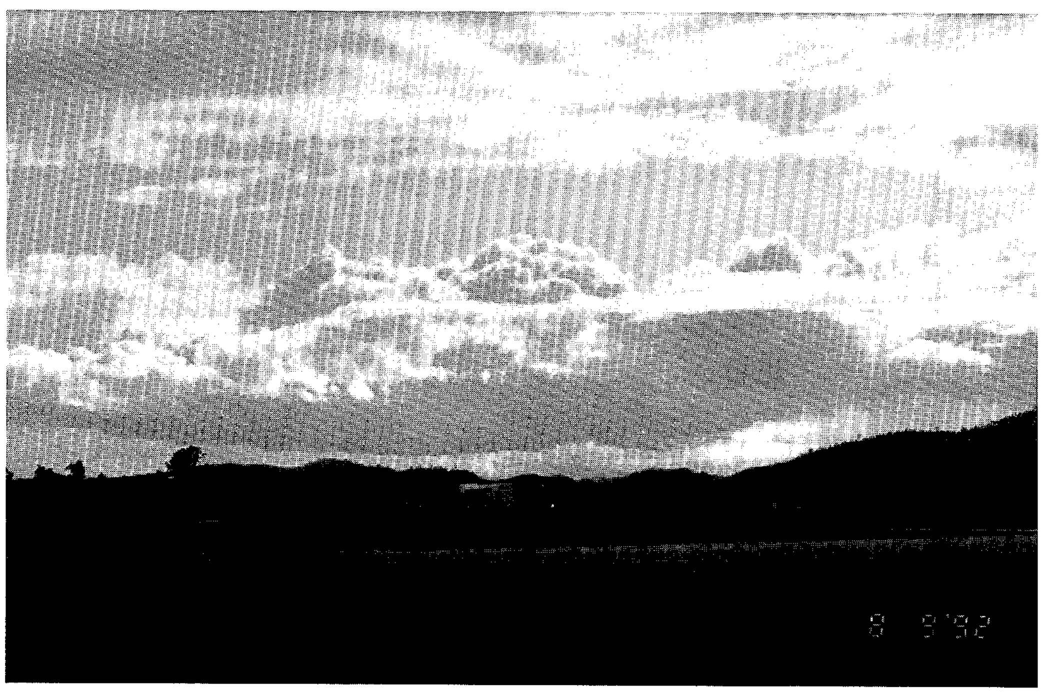

Figure 7.3. - Example of warm convective clouds near Chiang Mai, Thailand.

8. PROBLEMS AND LESSONS LEARNED

8.1 Implementation Problems

In carrying out the AARRP, the time spent accomplishing project tasks was longer than anticipated, which often caused problems and delays in the overall AARRP implementation. These delays caused correspondingly larger delays in accomplishment because of the dependence on field studies which must be conducted during specific periods of the year when appropriate weather conditions occur. In retrospect, the implementation schedule set forth at the start of the AARRP was probably unrealistic. The schedule was a product of Western thinking, which did not fully appreciate or account for the Thai "way of doing things." The Thai way is different than the Western way, not necessarily better or worse, but certainly different. There were four main reasons why the project took longer than expected by Western standards to implement: 1) organizational culture, 2) limited personnel availability, 3) not enough communication, and 4) not enough team work.

8.1.1 Organizational culture

1. The AARRP decisionmaking process operated through a hierarchy of committees in accordance with Thai rules and regulations. Decisionmaking was, therefore, a deliberate and time-consuming process, and no mechanism for expediting this process appeared to exist. Several key project activities required Thai Parliament approval.

2. Five-year plans and time constrained activities are Western society concepts. When an AARRP task was undertaken, it was pursued to a successful conclusion without regard to time constraints.

3. Delegation of authority is a primarily Western society concept, and did not appear to be an integral part of the AARRP organizational culture. The RRRDI Director made all local decisions and assignments and approved all local actions; these tasks were done only after project level decisions were made by the AARRP Director and/or the AARRP Steering Committee. In addition, AARRP decisions requiring that Thai funds be spent differently than originally budgeted had to be approved by the Bureau of Budget as well as AARRP officials.

8.1.2 Personnel

1. Perhaps the most important obstacle to more rapid progress was the limited number of personnel that could be assigned to the AARRP; the RRRDI also had to conduct their ongoing operational cloud seeding projects.

2. Another important obstacle to more rapid progress was the even more limited number of personnel with meteorological backgrounds who were capable of benefitting immediately from the technical assistance and training by the foreign experts.

3. The personnel problem was particularly acute during the period when the Thai scientists participated in long-term university training in the U.S. As a consequence, one person was assigned more than one project task, and project tasks had to be performed in tandem rather than in parallel. This problem had a particularly profound effect on the time of accomplishment of tasks that depended on the results of other related tasks.

8.1.3 Communications

1. Formal meetings of project committees and project personnel were the principal vehicles for exchanging information about project problems and the results of activities/studies in progress. Formal meetings to resolve problems were held as needed, but formal meetings to discuss the results of ongoing activities were not held frequently enough to serve the needs of the project.

2. More important, informal sharing of project information and results of activities/studies in progress between AARRP personnel and foreign experts or among AARRP personnel themselves was not frequent enough to account for the lack of formal meetings. The foreign experts learned of the status of ongoing activities primarily as a response to direct questions posed by them or inadvertently through related questions. The foreign experts were the primary link between AARRP personnel working on interrelated and interdependent activities; however, they could not be in-country often enough to accomplish this communication on a timely basis.

8.1.4 Teamwork

1. AARRP personnel preferred to work individually, rather than as members of a team.

2. AARRP personnel performed their tasks well, but most did so with no sense of urgency, and no sense of the interdependency between related tasks.

8.2 Technology Transfer Problem

AARRP personnel were, in general, eager to learn about modern weather modification technology and were enthusiastic about applying their new-found knowledge; however, in many cases they were ill-equipped to do so. Thus, AARRP personnel took longer to master the performance of tasks where alternate courses of action depended on intermediate scientific decisions, as is required in the conduct of rainmaking research and experimentation. They encountered particular difficulty in the conduct of project analyses and evaluation studies.

8.3 Technical Problem

During the 1993 AARRP field season, some problems occurred with the TMD's 0000 GMT (0700 LST) Chiang Mai soundings. On some days, the Chiang Mai soundings appeared to be either significantly too warm or too cold, and the problem became more pronounced above the 500-millibar level. On other days, the 0000 GMT Chiang Mai sounding data were similar to the Omkoi data, and apparently were correct.

An inconsistent problem apparently exists with the TMD equipment and/or methodology at Chiang Mai for the 0000 GMT sounding. The problem has not yet been identified. A visit to the TMD facility revealed that *different equipment and a different type of sonde* are used by the TMD for the 1200 GMT and any special soundings. This second system produces a strip chart that must be reduced manually. Although more time is required to process the data from this system, the resulting sounding data appear to be more accurate than data obtained with the system used for the 0000 GMT sounding.

9. SUMMARY AND RECOMMENDATIONS

Over the 6-year period from the beginning of the AARRP with the signing of the USAID-Reclamation PASA in early 1988, until the completion of the PASA at the end of March 1994, the combined RTG and U.S. contributions totaled $10,355,972. This total is comprised of $6,117,072 from the RTG (table 3.1) and $4,238,900 from the U.S. (table 4.2). The AARRP Phase 1 was originally scheduled to be completed at the end of 1992; however, the project was interrupted by a suspension to the PASA in October 1991. The PASA was reinstated in November 1992, with the ending date subsequently extended through March 1994. The RTG has committed an additional $2,800,000 for the period from April 1, 1994, through September 1995, for starting Phase 2 of the AARRP.

Delays in the implementation of AARRP project plan, as first set forth in 1988 (see section 8), resulted in the following changes:

1. Relaxation of the Project Goal including less comprehensive objectives:

changed from:

"The goal of the program is to increase manageable water resources in Thailand *through the implementation of a scientifically-based weather modification project on a demonstration basis*. The project will lead to improvements in current cloud seeding operations that are conducted to provide limited relief to economic and social impacts of local droughts by seeding promising clouds to increase rainfall over small but critical portions of the country. The program represents a demonstration and test program of improved technology, so emphasis will be placed on evaluation of project results to determine the feasibility of long-term weather modification application as a water resources management technique in Thailand."

changed to:

"The goal of the program is to provide the Royal Thai Government with the capability to conduct a scientifically sound demonstration project to quantify the water augmentation potential of rainmaking in Thailand. The program involves the conduct of field research and studies *leading to the development of a design and operations plan for the rainmaking demonstration project*, and the provision of equipment and training to plan and carry out the demonstration project."

2. Elimination of key project components including:

- Socioeconomic impact studies
- Environmental impact studies
- Pilot agricultural drought warning study
- Analysis training

As a result of the PASA, the AARRP succeeded in providing the Royal Thai Government with a design and operations plan for a warm and cold cloud seeding demonstration project to quantify the water augmentation potential of rainmaking in Thailand (see volumes 2 and 3, respectively). The project for carrying out the demonstration project design and operations plan that were developed under the AARRP is called the TRMDP (Thailand RainMaking Demonstration Project), or AARRP Phase 2.

All equipment to carry out AARRP Phase 2, including a Doppler weather radar, an aircraft data collection system, recording rain gauges, computers, and various other cloud seeding support equipment, has been delivered and installed. Training has been provided on the operation and maintenance of this equipment, and except for additional experience and occasional technical advice in critical situations, Thai personnel are now fully capable in this area. Five Thai project personnel were sent for graduate training in atmospheric sciences at universities in the U.S. The Thai students have returned to Thailand and those that successfully completed their studies have assumed leadership positions in the AARRP. In addition, most in-country training on conducting experimental operations and data collection has been completed. Additional technical assistance and training is needed to enable Thai scientists to execute the demonstration project operations plan in strict accordance with the demonstration project design.

Thai personnel are now fully capable of conducting field research and experimental activities, but additional technical assistance and training is needed to enable them to fully master the decisionmaking capability associated with the conduct of these field activities. In-country training on data analysis and experimental evaluation was only started, and significant additional technical assistance and training are needed to enable Thai scientists to acquire a full capability in both the operations and scientific decisionmaking aspects of this important component of the project. Thai scientists are not yet capable of analyzing, evaluating, and interpreting the results of the demonstration project without additional technical assistance and training; they have not yet been provided with all the planned training in these scientific disciplines for reasons given in section 8, nor have they been provided with all the scientific software needed to accomplish these tasks.

Table 9.1 provides a summary and assessment of capabilities achieved under the AARRP, and indicates what is needed to maximize these capabilities. The capability to conduct operations (field activities and analyses), and to make associated scientific decisions is assessed separately.

It is recommended that this three-volume final report be translated into the Thai language in order to enable AARRP scientists and interested Thai officials to fully understand these AARRP results and their implications for the future of Thailand's rainmaking program. Specific recommendations are given below under four categories: 1) programmatic, 2) technical, 3) scientific, and 4) institutional.

9.1 Programmatic Recommendations

1. *It is strongly recommended that the MOAC enter into a 5-year contract with a U.S. firm having AARRP experience and expertise in dynamic, cold cloud seeding in order to acquire continued professional services in support of the implementation of the projected 5-year duration of AARRP Phase 2.* This will be the first time that Thai personnel will be conducting and evaluating a scientifically rigorous experimental seeding operation such as the AARRP Phase 2. Technical oversight, guidance, quality control, and technical assistance are needed to enhance Thai capabilities, to promote personnel confidence in their capabilities, and to maintain the integrity of the experiment so the results are scientifically credible and acceptable by the RTG and the international scientific community. In particular, training in the analysis, evaluation, and interpretation of the results of experiments, such as AARRP Phase 2, must be completed; this training will be most effective if it is conducted in the

context of the demonstration project. Table 9.2 provides a summary of technical assistance and training that is needed and should be provided during AARRP Phase 2.

IF AND ONLY IF THE ABOVE RECOMMENDATION IS ADOPTED:

2. *It is recommended that the MOAC implement AARRP Phase 2 as soon as possible.*

3. *It is recommended that the RTG take a leadership role among the ASEAN nations in the organization and conduct of an ACRP (Asean Cooperative Rainmaking Project).* The centerpiece of the ACRP should be Thailand's warm and cold cloud seeding demonstration project (AARRP Phase 2). All ASEAN nations should be invited to actively participate in a way that enhances the conduct of the AARRP Phase 2 and, at the same time, enhances each participating nation's national rainmaking program.

IN THE EVENT THAT THE FIRST RECOMMENDATION IS NOT ADOPTED:

1. *It is recommended that the MOAC* ***not*** *implement AARRP Phase 2 or the ACRP.*

9.2 Technical Recommendations

Recommendations to strengthen the technical component of the AARRP are as follows:

1. *It is recommended that the MOAC purchase and install a CCN counter at the AARRP radar site near Omkoi, Thailand.* The CCN counter should be operated routinely on a 24-hour basis. The CCN counter is urgently needed to evaluate the impact of crop and forest burning on the natural rainfall in northern Thailand, and to determine the feasibility of hygroscopic flare seeding. By making these measurements, Thailand could be a participant in the international nuclei measurement program.

2. *It is strongly recommended that the MOAC establish a maintenance contract for the AARRP radar, through which a radar engineer fully knowledgeable with the AARRP radar could provide technical advice and, as required, be sent to Thailand to perform critical repairs.* Perhaps the biggest problem in obtaining the required sample size in the rainmaking demonstration project in the projected number of years is the potential for extended downtime of the radar, the principal source of data in the evaluation. AARRP radar failure during 1993 resulted in about 3 months downtime and was fixed only after it was decided to bring in an EEC engineer under PASA funding. This failure precluded the conduct of the preliminary warm cloud seeding experiments in 1993.

3. *It is recommended that the MOAC establish a maintenance contract for the Airborne Cloud Physics Measuring System, through which a knowledgeable engineer could provide technical advice and, as required, be sent to Thailand to provide critical technical services.* Such a contract would be particularly important if and when the AeroCommander is replaced by another aircraft, and the Airborne Cloud Physics Measuring System installation has to be re-engineered for the replacement aircraft.

4. *It is recommended that the MOAC enter into a formal agreement with NASA through which NASA will continue to provide rain gauge spare parts and replacements, radar*

recorder spare parts and replacements, training, and incidental operating expenses in return for copies of recorded radar and rain gauge data. This agreement will enable Thailand's continued participation in the international TRMM program.

5. *It is recommended that the MOAC reconfigure the existing rain gauge network as proposed in "Volume 3 - Demonstration Project Operations Plan."*

6. *It is recommended that the MOAC improve their $CaCl_2$ handling and storage procedures in an effort to maintain the particle size spectra as close as possible to that originally delivered by the manufacturer.*

7. *It is recommended that the MOAC pursue the development or purchase of a hygroscopic particle dispensing system for the warm cloud seeding demonstration project.* The dispenser should be capable of ejecting sized hygroscopic seeding particles from the aircraft at rates ranging from 75 to 375 kilograms per minute. The dispenser should contain some kind of device, like a stirrer or agitator, which will reduce the clumping of the hygroscopic particles.

8. *It is recommended that the MOAC establish data management and archival procedures as proposed in "Volume 3 - Demonstration Project Operations Plan."*

9.3 Scientific Recommendations

Recommendations to strengthen the scientific component of the AARRP are as follows:

1. *It is recommended that the RTG further investigate the cause of the changes in the rainfall-inflow relationships described in appendix F of "Volume 2 - Demonstration Project Design," and the effect of these changes on the water management of northern Thailand.*

2. *It is recommended that the MOAC pursue the feasibility of hygroscopic flares as a viable rainmaking technique.* If feasible, it would be considerably less expensive than hygroscopic particle seeding. However, it must be proven feasible through the CCN measurements recommended above, and by demonstrating that the seeding can be performed effectively and safely.

3. *It is recommended that additional numerical modeling and field studies as proposed in Volume 2 be conducted as a part of the warm cloud seeding demonstration project.* These studies should focus on obtaining a better understanding of the chain of physical events following hygroscopic particle seeding of warm and cold convective clouds.

4. *It is recommended that the MOAC further develop the preliminary objective forecasting technique for cloud top height described in volume 2, appendix C, to improve its accuracy and reliability.* The following steps are recommended: a) conduct an operational test using the equation obtained for the 54-day sample and compare with the observed 95-percentile radar echo tops over the eastern target areas; b) analyze the radar echo top data for the 54-day sample using different percentiles of observed radar echo tops, reducing the percentile value until the percentile is found that eliminates the higher echoes from cold clouds; c) rerun the MLR analysis on the 54-

sounding sample data set using radar echo tops at the percentile that produces representative samples of days with warm and cold cloud tops; and d) redo the correlation and MLR analysis study (steps a through c) using a larger sample size. This procedure will increase the stability of the statistical analyses, and will also allow analyses of pre-monsoon and monsoon data subsets. Only days that have good quality Chiang Mai 0000 GMT soundings to at least the 150-millibar level, and good AARRP radar data, can be included in this larger sample.

5. *It is recommended that the MOAC contact the TMD's station chief at Chiang Mai for the purpose of: 1) providing evidence that a problem exists with the 0000 GMT sounding data, 2) offering assistance in trying to identify the problem, and 3) suggesting that the second TMD sounding system, which is used for the 1200 GMT soundings, should also be used for the 0000 GMT soundings until the problem is identified and corrected.* Good rawinsonde data are essential for input to the GPCM (Great Plains Cumulus Model) and ANALYZR; consequently, all of the soundings must be carefully quality controlled. The rawinsonde data occasionally include bad data points, which can be easily identified on the plotted soundings and then corrected.

9.4 Institutional Recommendations

Recommendations to strengthen the institutional component of the AARRP are as follows:

1. *It is recommended that the MOAC establish an Advisory Board for the AARRP Phase 2 to provide oversight, technical guidance, and problem solving during the implementation of the demonstration project.* Members of the Advisory Board should include university professors with expertise in atmospheric sciences, statistics, and chemistry.

2. *It is recommended that the MOAC improve personnel availability to the AARRP Phase 2, and that they provide mechanisms for improved communications and team work.*

3. *It is strongly recommended that the AARRP scientists improve their programming (e.g., FORTRAN) and/or hire a programmer.* A programming capability is vital to the AARRP Phase 2 analysis and evaluation effort.

Table 9.1. - Assessment of AARRP capabilities.

Item	Activities	Capability: Operations Target	Capability: Operations Achieved	Capability: Sci Decisionmaking Target	Capability: Sci Decisionmaking Achieved	Needs	Recommendations
1. Core training	A. Applied weather modification, experimentation, anal/evaluation	100%	80%	100%	80%	Experience Tech advice	
2. Equipment	A. Installation	100%	100%	N/A	N/A	Cloud condensation counter	Purchase 1 unit (note 1)
	B. Operations	100%	80%	80%	80%	Experience Tech advice	Continue operations
	C. Maintenance	100%	80%	80%	60%	Experience Tech advice Refresher train	Yearly refresher In maintenance/ calibration (note 2)
	D. Opn'l software	100%	80%	100%	80%	Experience Tech advice	Continue operations
3. Data collection & processing	A. Operations	100%	80%	80%	60%	Experience Tech asst/train	(note 3)
	B. Opn'l software	100%	80%	80%	60%	Experience Tech asst/train	(note 3)
	C. Field data processing	100%	80%	80%	60%	Experience Tech asst/train	(note 3)
	D. BRRAA data management	60%	40%	40%	20%	Experience Tech asst/train	(note 3)
4. Cold cloud experiment	A. Experimental procedures	90%	80%	80%	70%	Experience Tech asst/train	(note 3)
	B. Qualification of expt'l units	90%	80%	80%	50%	Experience Tech asst/train	(note 3)
	C. Seeding execution	90%	80%	80%	50%	Experience Tech asst/train	(note 3)
	D. Quality control	90%	80%	80%	50%	Experience Tech asst/train	(note 3)
5. Warm cloud experiment	A. Experimental procedures	90%	80%	80%	70%	Experience Tech asst/train	(note 3)
	B. Qualification of expt'l units	90%	80%	80%	50%	Experience Tech asst/train	(note 3)
	C. Seeding execution	90%	80%	80%	50%	Experience Tech asst/train	(note 3)
	D. Quality control	90%	80%	80%	50%	Experience Tech asst/train	(note 3)
6. Data analysis & experimental evaluation	A. Software, procedures & interpretation	60%	40%	20%	10%	Experience Tech assistance Collaboration	(note 4)
	B. Reports/papers	60%	40%	20%	10%	Experience Tech assistance Collaboration	(note 4)

Note 1: Suppliers of CCN counters will be provided upon request.
Note 2: Radar is essential for operations and evaluation; poor data and downtime prolong the experiment.
Note 3: In-service training with foreign experts.
Note 4: Scientific collaboration with foreign experts.

Table 9.2. - Technical assistance and training during AARRP Phase 2 (1994-1998).

Subprogram	Activities	Days Required: Thailand	Days Required: Total	Target Outcome	How Success Measured
1. Cold Cloud Demonstration Project	A. Field operations assistance, quality control, training	206	294	100% independent capability by 1997; quality control thereafter	Acceptable experimental units qualified independently
	B. Data collection, reduction, analysis; experiment eval.; quality control; and training	130	360	100% independent capability by 1998	Improvement in research quantity, quality, and importance
	C. Collaborative research	76	109	Thai scientists publish scientific papers in peer review journals	Publish at least one scientific paper per year, first as coauthors, then as senior authors
Subprogram 1—days		412	763		
2. Warm Cloud Demonstration Project	A. Field operations assistance, quality control, training	206	294	100% independent capability by 1997; quality control thereafter	Acceptable experimental units qualified independently
	B. Data collection, reduction, analysis; experiment evaluation; quality control; and training	130	360	100% independent capability by 1998	Improvement in research quantity, quality, and importance
	C. Collaborative research	76	109	Thai scientists publish scientific papers in peer review journals	Publish at least one scientific paper per year first as coauthors, then as senior authors
Subprogram 2—days		412	763		
Total Program—days		824	1526		

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Final Report
Volume 2

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16. ABSTRACT

This final report, prepared by the Bureau of Reclamation under the PASA, consists of three volumes. Volume 1 includes a summary of the AARRP structure, the contributions to the AARRP by the U.S. and the Royal Thai Governments, and the institutional development, technology transfer, technical, and scientific accomplishments. Volume 1 concludes with a summary of problems encountered, lessons learned, and recommendations for the future. Volume 2 presents a detailed account of the scientific studies and their findings, and provides the design of the demonstration project (also known as AARRP Phase 2). Volume 3 presents the operations plan for the demonstration project.

Results of the AARRP cloud modeling and field studies suggest that increasing rainfall by static, warm cloud seeding with hygroscopic particles and by dynamic, cold cloud seeding with silver iodide are scientifically promising. A definitive warm and cold cloud seeding demonstration project to quantify the water augmentation potential of these rainmaking techniques in Thailand is warranted and recommended as the next logical AARRP activity. This PASA has provided a design and operations plan for the proposed demonstration project, as well as the equipment needed to carry it out. Training in the operation, maintenance, and use of this equipment for field experiments has also been provided; however, training in the scientific decisionmaking associated with the execution of the required seeding procedures was not completed, and training in the analysis, evaluation, and interpretation of experimental results was only started. As a result, Thai scientists are not yet capable of implementing the proposed demonstration project on their own. Therefore, it is recommended that the demonstration project be implemented *if and only if* the MOAC continues foreign technical assistance to 1) ensure that the demonstration project is carried out in strict accordance with the proposed design following international scientific standards, 2) complete the technology transfer and training started under the AARRP and provide the Thai scientists with a full capability to plan, conduct, monitor, and evaluate rainmaking projects, and 3) transfer the demonstration project seeding technology to Thailand's operational rainmaking program.

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THAILAND APPLIED ATMOSPHERIC RESOURCES RESEARCH PROGRAM

Final Report
Volume 2

Demonstration Project Design

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March 1994

UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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DEDICATION

This report is dedicated to His Majesty King Bhumibol Adulyadej, who provides spiritual and scientific leadership for Thailand's program of rainmaking.

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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GLOSSARY AND ACRONYMS

AARRP: Applied Atmospheric Resources Research Project.

ACRP: ASEAN Cooperative Rainmaking Project.

AgI: silver iodide.

a.g.l.: above ground level.

ASEAN: Association of Southeast Asian Nations.

ATT: Agricultural Technology Transfer Project.

BRRAA: Bureau of Royal Rainmaking and Agricultural Aviation.

Cb: cumulonimbus.

CCL: convective condensation level.

CCN: cloud condensation nucleus.

$CaCl_2$: calcium chloride.

Cold cumulus cloud: a large cumulus cloud whose top rises above the 0 °C level and in which precipitation development by ice particle growth processes is dominant. If the cloud top temperature reaches -10 °C to -25 °C, the cloud becomes suitable for glaciogenic seeding.

Convective cell: the basic element of convective cloud systems, consisting of a single updraft and down draft couplet. The convective cell has been selected as the treatment unit of the 1991 AARRP experiments.

DAS: data acquisition system.

DTEC: Department of Technical and Economic Cooperation.

"Dynamic Seeding": seeding whose primary purpose is to invigorate the internal circulations that sustain the cloud, force the ingestion and processing of more water vapor, leading to larger or more long-lived clouds and increased rainfall.

EEC: Enterprise Electronics Corporation.

EGAT: Electricity Generating Authority of Thailand.

Experimental unit: the convective elements, convective cells, and small multiple-cell convective systems within a circle having a radius of 25 kilometers and centered at the location of the convective cell that qualified the unit for treatment.

FACE: Florida Area Cumulus Experiment.

FOC: AARRP Field Operations Center at the RRFRC.

FOD: AARRP Field Operations Director.

GMS: geostationary meteorological satellite.

GMT: Greenwich mean time.

GPCM: Great Plains Cumulus Model.

GPS: global positioning system.

Glaciogenic seeding: seeding of a cloud with ice-forming chemicals to bring about the conversion of its supercooled water to ice.

IAS: indicated airspeed.

IRIS: Interactive Radar Information System.

"Metwatch": Frequent visual observations of cloud conditions over the AARRP study area, especially the development of convective clouds.

MCM: millions of cubic meters.

MLR: multiple linear regression.

MNR: maximum natural rainfall.

MOAC: Ministry of Agriculture and Cooperatives.

MRPP: multi-response permutation procedure.

m.s.l.: mean sea level.

NASA: National Aeronautics and Space Administration.

Non-operational day: a non-operational day is declared by the Field Operations Director when it is desired to give all AARRP personnel time off; generally, the declaration will be made the previous day.

"Nowcasting": a close meteorological surveillance of the project area to determine the weather conditions that already exist and those that are expected to exist in the next 2 hours.

Operational-go day: an operational-go day is declared by the Field Operations Director when convective cloud systems that are likely to be suitable for warm and/or cold cloud seeding exist in the study area, indicating that randomized cloud seeding experiments should commence as soon as possible.

Operational-standby day: an operational-standby day is declared by the Field Operations Director when conditions suitable for randomized seeding experiments do not exist in the study area now, but are expected to develop within the next 2 to 6 hours.

Operational-stand down day: an operational-stand down day is declared by the Field Operations Director when it is desired to suspend operations for the high altitude aircraft crew and the rawinsonde team for the 1300 LST (local standard time) sounding; all other project activities should be continued.

PASA: participating agency service agreement.

PCWG: project coordinator working group.

PDF: probability density function.

PE: precipitation efficiency.

PRF: pulse repetition frequency.

Randomization: a process in experimentation whereby what is to be done to a treatment unit is determined randomly from a set of treatment decisions. Prior to experimentation, the treatment decisions are generated by a mathematical process that ensures that the assignment of treatment is truly random.

Randomized research day: a randomized research day for warm and/or cold cloud seeding is declared after aircraft penetrations of convective clouds establish that suitable conditions are present and that randomized seeding operations are about to begin.

Reclamation: Bureau of Reclamation.

RFC: Regional Forecast Center.

RRFRC: Royal Rainmaking Field Research Center at Chiang Mai Airport.

RRRDI: Royal Rainmaking Research Development Institute of the Kingdom of Thailand.

RSA: resident scientific advisor.

RTG: Royal Thai Government.

Small multiple-cell convective system: a radar echo containing two or more reflectivity maxima or cells, generally within a common echo boundary, but having no horizontal dimension greater than 100 kilometers.

"Static Seeding": seeding to increase rainfall by improving the precipitation efficiency of the cloud.

Study area: the area in northwest Thailand over which randomized seeding operations may be conducted. A map of this area is provided in the main portion of this report.

SLWC: supercooled liquid water content.

SMF: seeding multiplicative factor.

SWCP: the Southwest Cooperative Project that has been conducted in West Texas during portions of the summers of 1986, 1987, 1989, and 1990. This program is continuing.

TAS: true airspeed.

TCu: towering cumulus.

TRMDP: Thailand Rain Making Demonstration Project.

TRMM: Tropical Rainfall Measuring Mission.

TMD: Thai Meteorological Department.

Treatment: The result of the randomization scheme which determines what action is to be taken upon the experimental unit. The treatment will be either to seed convective cells within the experimental unit or to consider the experimental unit as a control and conduct simulated treatment.

Treatment unit: a convective cell within the experimental unit which meets the seeding criteria of liquid water content and updraft speed. The convective cell receives the treatment (actual or simulated) and is the cell in which any treatment effect should first be detected.

TWG: Technical Working Group of the AARRP.

USAID: U.S. Agency for International Development.

VOR/DME: very high frequency omni range/distance measuring equipment.

Warm Cloud: a cumulus cloud whose top never rises above the 0 °C level, and in which precipitation development by collision and coalescence processes is dominant.

WMO: World Meteorological Organization.

WWC: Woodley Weather Consultants.

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1. INTRODUCTION

The Weather Modification Assessment: Kingdom of Thailand (Silverman et al., 1986) recommended a comprehensive 5-year developmental program to improve the technical capabilities of the RRRDI (Royal Rainmaking Research Development Institute) through training, additional equipment, and a demonstration cloud seeding project. USAID (U.S. Agency for International Development) accepted these recommendations, and a new, broadly-based program known as the AARRP (Applied Atmospheric Resources Research Program) was established.

Subsequent to the report by Silverman et al. (1986), a core training course was conducted in February and March 1988 to acquaint AARRP participants with the scientific principles, terminology, and technology of weather modification as a water augmentation tool. Simultaneous with and following this training, a number of studies were conducted in preparation for the demonstration cloud seeding project. These studies are described in a report by Medina et al. (1989).

The basic concepts to be tested in Thailand, including hygroscopic particle seeding of warm clouds to increase rainfall and cold cloud seeding to produce dynamic effects and increased rainfall, were investigated using a hierarchy of cloud models. The model runs indicated that both seeding approaches have potential for increasing rainfall in Thailand and that perhaps 35 percent of the potential operational days might be suitable for seeding for dynamic effects.

Preliminary design work on the demonstration project design extended beyond the numerical studies of possible responses to seeding. After visiting potential experimental sites, officials of the RRRDI and Reclamation (Bureau of Reclamation) selected the southern part of the Bhumibol catchment area of northwestern Thailand for the conduct of the demonstration project (see fig. 1.1). The FOC (Field Operations Center) was located initially at the Bhumibol Dam site, and an S-band (10-centimeter) Doppler weather radar was installed at a site about 9 kilometers southeast of Omkoi on a ridge (height 1,162 m) which provides a good view of the southern catchment area drainage. The FOC was moved to Chiang Mai Airport in Chiang Mai, Thailand, in 1992, and was organized to obtain necessary data for weather forecasting and monitoring.

Aircraft were outfitted for hygroscopic and glaciogenic seeding. The high-altitude cold cloud seeder aircraft was also equipped for meteorological data collection, including some basic measurements of cloud physics (e.g., temperature, dew point temperature, cloud liquid water, and cloud drafts). A network of rain gauges was installed in the project area, which is being used with the radar to obtain rain gauge adjusted radar rainfall estimates. These data will provide the basis for physical and statistical evaluation of project experiments.

The report by Medina et al. (1989) concluded by recommending that a number of theoretical and related field studies be conducted prior to commencement of the warm and cold cloud demonstration projects because the information sought is important to the project design. Most important were studies to better define cloud seeding potential, including the number and character of seeding opportunities based on physical observations and model runs. The report proposed that the AARRP satellite imagery, rain gauges, radar, rawinsondes, hydrologic data, and a cloud physics aircraft provide the needed observations.

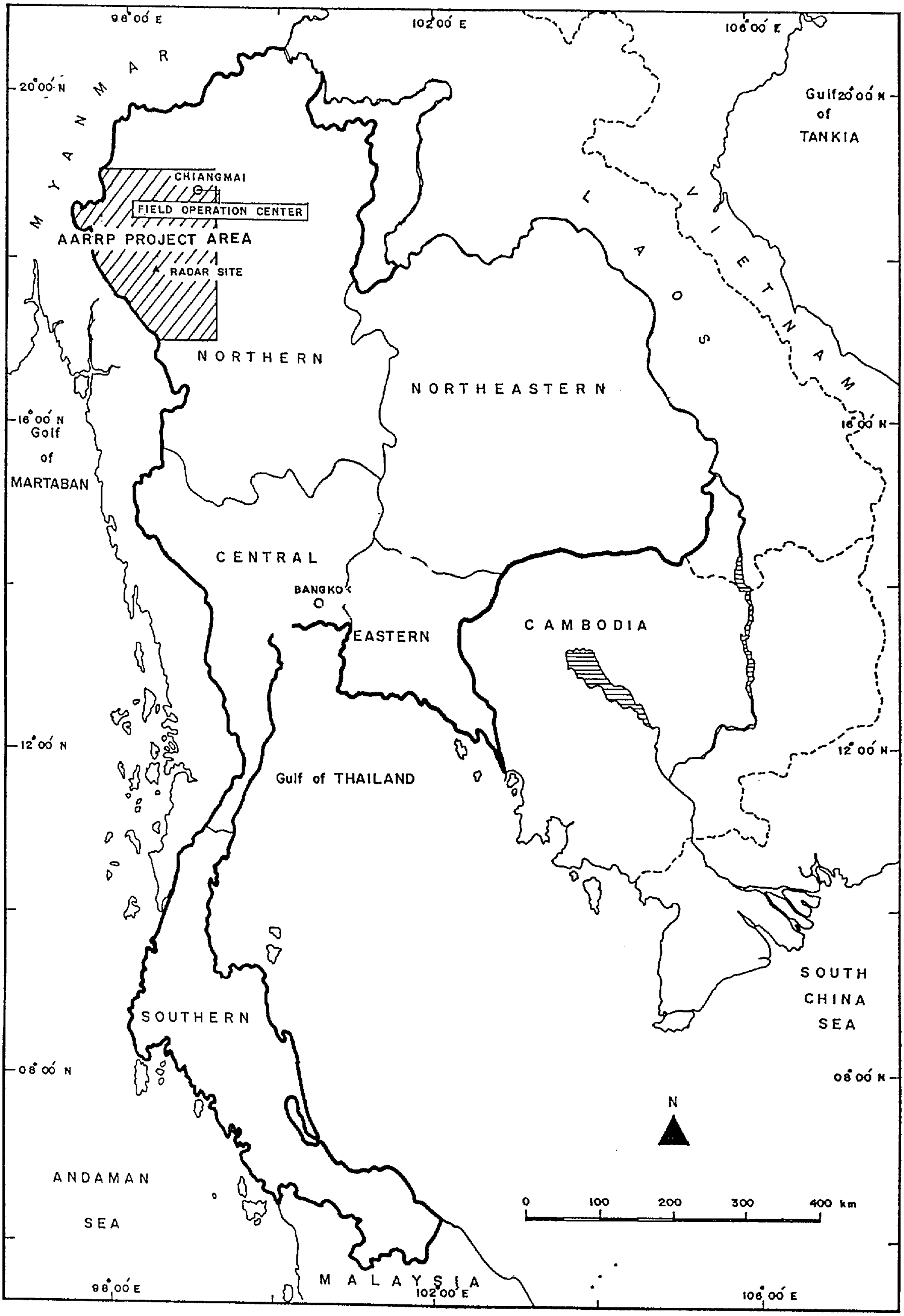

Figure 1.1. - Map of Thailand showing the area recommended for field studies and experimentation.

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Many of the recommended studies have been completed, including commencement of the cold cloud experiment. This report describes the findings of these studies and the resulting demonstration project design.

Delays in the implementation of the AARRP project plan, as first set forth in 1988, resulted in the relaxation of the Project Goal to one with less comprehensive objectives and the elimination of several key project components, including socioeconomic impact studies, environmental impact studies, the pilot agricultural drought warning study, and analysis training.

Weather modification for rain enhancement is obviously a major undertaking that is not to be taken lightly if it is to be done properly. A thorough discussion of the scientific challenges that must be met in designing, conducting, and evaluating a scientifically-based cloud seeding experiment is provided in appendix A.

2. DESIGN OF THE THAI COLD CLOUD RAINMAKING DEMONSTRATION PROJECT

2.1 Statement of the Problem

The question to be addressed is whether the seeding of vigorous supercooled convective clouds with an ice nucleant over a moveable area, covering nearly 2,000 square kilometers, can produce substantial and statistically significant increases in rainfall over that area. The larger question is whether this proposed methodology might be used to assist Thailand in managing its water resources.

2.2 Principles of Cold Cloud Seeding for Rain Enhancement

People have long dreamed of changing the weather, particularly the precipitation from clouds. Not until the middle of the 20th Century, however, with the discovery of the ice-nucleating properties of dry ice (Schaefer, 1946) and AgI (silver iodide) (Vonnegut, 1947) did this dream approach reality. Tested first in the cold box and later in supercooled-water clouds, dry ice and AgI acted to convert all or a portion of the supercooled water to ice crystals. When tested in supercooled cloud layers, these artificially-induced ice crystals grew and fell from the clouds as precipitation. Before treatment, the clouds contained high concentrations of supercooled water drops, which were too small to fall from the cloud. These drops remained supercooled, despite temperatures below 0 °C, because of a deficiency in natural ice nuclei. Only after seeding did precipitation occur. The enhancement of precipitation initially seemed as simple as supplying supercooled clouds with artificial ice nuclei to make up for the deficiency in natural ice nuclei. Reality has proved to be much more complex.

Braham (1985) points out that the science of cloud seeding for rain enhancement in mixed-phase cloud (i.e., consisting of water and ice particles) rests on four established facts and two postulates. The first fact is that water drops remain unfrozen in some clouds at temperatures below 0 °C. The second fact is that the saturation vapor pressure over ice is less than that over supercooled water at the same temperature, which allows ice particles in a supercooled cloud to grow by vapor deposition while the droplets evaporate. The third fact is that precipitation in many areas of the world comes from mixed phase clouds. The fourth fact is that a large number of artificial ice nucleants have been discovered. Those nucleants used most commonly in cloud seeding experiments are dry ice (frozen carbon dioxide) and AgI. A new organic seeding agent (*Pseudomonas Syringae*), consisting of deactivated, harmless, natural bacteria, has been tested recently in the United States (Woodley and Henderson, 1989). The major advantage this agent has is that it begins to work as an ice nucleant at temperatures as warm as -1 °C; AgI becomes active at temperatures below -4 °C.

The first postulate is that a shortage of ice nuclei limits the PE (precipitation efficiency) of some supercooled clouds to as low as 20 percent for some continental thunderstorms. Some supercooled clouds do not precipitate at all. Such clouds are potential targets for glaciogenic seeding.

Attempts to increase rainfall by improving precipitation efficiency are called "static" seeding, or seeding for microphysical effects. Any concomitant change in cloud dynamics is assumed to be small and of no consequence with this seeding approach. Ice nucleus concentrations on the order of 1 to 10 per liter are thought to be optimal.

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The second postulate centers on the observation that the updraft regions of convective clouds frequently contain substantial amounts of supercooled liquid water. If this water can be frozen at a faster rate and at warmer temperatures than would have occurred naturally, the latent heats of fusion and deposition will be released, leading to increased cloud buoyancy and greater cloud growth. (Note: Depositional heating does not always add to cloud buoyancy; Orville and Hubbard, 1973) This larger cloud would then process more water vapor, leading to increases in precipitation.

The second postulate is called "dynamic" seeding, or seeding for dynamic effects. With this approach, concentrations of ice nuclei on the order of 100 per liter are thought optimum. This approach is called "dynamic" because the primary result of seeding is the invigoration of the internal circulations that sustain the cloud and the ingestion and processing of more water substance. In theory, at least, this approach can lead to the precipitation of more water than was present in the cloud at the time of seeding.

In reality, neither approach to seeding for rain enhancement produces only "static" or "dynamic" effects. All cloud processes are interactive. For example, microphysical changes (e.g., rapid glaciation) are a prerequisite for the production of dynamic effects, and dynamic changes (e.g., increased updraft) are necessary for the production of more cloud condensate. The cloud processes leading to precipitation are far more complex and interactive than was believed at the time these seeding concepts were being developed. For ease of reference, the terms "static" and "dynamic" seeding are still used to indicate whether the primary purpose of the seeding is to induce microphysical changes that enhance precipitation efficiency, or to induce dynamic changes that enhance cloud size or duration, respectively.

By extrapolation from seeding experiments in climatologically similar areas and preliminary results from cloud model and field seeding experiments on Thai clouds, it has been concluded that the most promising cold cloud seeding concept for Thailand is dynamic-mode seeding.

2.3 Summary of Results Relevant to Thailand

The most systematic investigation of the potential of "dynamic seeding" for rainfall enhancement began in clouds over the Caribbean Sea in the mid-1960s (Simpson et al., 1967), and continued in Florida in the series of experiments that came to be called the FACE (Florida Area Cumulus Experiment). Although the FACE program did not provide conclusive proof that seeding had increased areal precipitation, the estimated rainfall increases ranged between 10 and 25 percent for the target area, covering 1.3 x 10^4 square kilometers and between 20 percent and 50 percent for groups of treated convective clouds within the target area (called the "floating target") (Woodley et al., 1982; 1983). The FACE program also provided strong evidence for substantial increases in rainfall from individual convective clouds and cells. The first experiments (in 1968 and 1970) indicated that the rainfall from individual clouds could be increased by over 100 percent (Simpson and Woodley, 1971). A major breakthrough in the second of the two experiments (1978 to 1980) was made with the development of a method to identify, track, and assess the properties of the treated clouds throughout their lifetimes. Use of this technique permitted a more comprehensive analysis of the effect of seeding on the individual convective cells. Again, the results indicated rain increases of over 100 percent (Gagin et al.,1986).

These results for tropical clouds in Florida provided the impetus for continuation of dynamic seeding research in Texas. The Texas research to date indicates that dynamic seeding has enhanced the rainfall from individual cells by over 100 percent, thereby replicating many of the Florida results. In addition, rain increases of over 50 percent are indicated for the experimental unit (i.e., the small mesoscale convective cluster) that covers nearly 2,000 square kilometers (Rosenfeld and Woodley, 1989; 1993).

Finally, an operational seeding program in West Texas has provided evidence of areal rainfall increases through dynamic seeding. This evidence comes from an assessment of five years of warm season cloud seeding over a watershed serving San Angelo, Texas (Woodley and Solak, 1989). Target-control regressions that had been derived from historical rainfall records were used to estimate the effect of dynamic seeding in this program. The analysis suggests more rainfall in each of the five years. The probability of this increase happening by chance is about 3 percent. An overall effect of seeding of about +17 percent for the target for all years of operation is indicated. Sensitivity testing supports the interpretation that seeding was responsible for a sizeable portion of this apparent rainfall increase.

In summary, the scientific evidence from cloud seeding research programs in Florida and Texas that have employed dynamic seeding techniques indicates that rainfall can be increased from convective clouds by over 100 percent on the scale of individual cells, by 25 to 50 percent on the scale of groups of convective clouds, and by 10 to 25 percent over targets up to 13,000 square kilometers in size. As the target size increases, the fraction of convective clouds within that target that are seedable and can be effectively seeded decreases. The strength of the evidence for enhanced rainfall decreases as the scale of the rainfall increases. The evidence is strongest for individual cells where the seeding signal is largest, and weakest for large target areas where the seeding signal is weakest. Much remains to be known as to how and why dynamic seeding works to increase areal rainfall, and this question is the basis for continuing research in the United States.

2.4 Summary of Thai Cold Cloud Seeding Experiments

2.4.1 Introduction

At the outset of the Thai cold cloud studies, all participants agreed that it would be a mistake to begin a full-scale area seeding experiment in Thailand based on what was known at the time about the microphysical and dynamic characteristics of Thai Clouds. Such experiments were felt to be too consumptive of time and money to warrant beginning with such an effort. On the other hand, the participants recognized that years of basic meteorological studies are not necessary before the potential of seeding can be evaluated. Too much is known from seeding experiments in other climatologically similar areas to require beginning "at first principles" in Thailand.

The components of the Florida (FACE) and Texas [SWCP (Southwest Cooperative Project)] studies that focused on the convective cell proved successful with relatively small samples, and they gave credibility to the overall effort. This result is not surprising when one considers that the building blocks of convective cloud systems are the individual convective elements, which consist initially of individual moist updrafts and later as downdrafts filled with precipitation. These convective elements are often seen visually as towering cumulus clouds and on radar as reflectivity cores or cells. Most of the water vapor feeding the cloud is ingested via its updrafts. This water vapor, which is condensed in the updraft, may be converted into precipitation particles, or it may be lost by mixing and evaporation into the ambient air.

In view of the accomplishments of the Florida and Texas cold cloud dynamic seeding programs, the techniques and approaches were transferred to the Thai situation through exploratory experiments that focused initially on convective cells. These Thai experiments were patterned closely after those that are continuing in Texas. The Texas design has worked extremely well in the field since its improvement in 1987, and the results of the program to date have been most gratifying (Rosenfeld and Woodley, 1989; 1993). Many reasons exist, therefore, to start in Thailand with this proven design.

The beginning point in the AARRP rain enhancement program, therefore, was the documentation of the primary seeding effect on the actually seeded entities, namely, the individual convective cells.

The question addressed with this approach was:

> "Does the glaciogenic seeding of suitable supercooled convective towers for the production of dynamic effects produce greater echo top-heights, areas, durations, and rainfalls in the cells in which these towers reside?"

If the answer to this question proved to be "yes," the way would be clear to proceed to the next step in developing a cold cloud, dynamic seeding, rain enhancement technology for Thailand. If the answer proved to be "no," then no basis would exist for proceeding further with this particular seeding approach. Confirming the potential in a short duration experiment on single convective cells was felt to be necessary before considerable time, effort, and resources were invested in a multi-year test of this seeding approach in enhancing area-wide rainfall.

2.4.2 Design of the Thai cold cloud seeding and its implementation

The Thai experiments were carried out in accordance with the Design Document and AARRP Operations Plans by Woodley et al. (1991). In every case, the experimental unit was the small, multiple-cell convective system within a circle having a radius of 25 kilometers and centered at the location of the convective cell which qualified the unit for treatment. The treatment decisions were randomized on a unit-by-unit basis, and all suitable convective cells within the unit received the same treatment—AgI in the case of an S (seed) decision or simulated AgI in the case of an NS (no seed) decision.

In the Thai design, therefore, the treatment units were the convective cells which contained cloud towers that met the liquid water and updraft requirements. The cell receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells. Additional information on the design of the Thai exploratory experiments is provided in appendix B.

During the randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical top heights of 6.0 to 7.0 kilometers and top temperatures of -7 to -9 °C). The seeding devices were dropable flares that produced 20 grams of AgI smoke during their 1-kilometer free-fall through the upper portion of the cloud. Between 1 and 10 flares normally were ejected during a seeding pass. The flare ejection button was pressed about every second while the cloud liquid water reading was greater than 0.5 gram per cubic meter and the aircraft was in updraft (the 1.0-gram-per-cubic-meter and 5-meter-per-second requirements applied only to the initial qualification pass). In some cases, seeding or simulated seeding was done 1,000 feet or less above the top of an especially vigorous hard tower when previous cloud passes on a particular day had established the suitability of the subject clouds. In the simulated seeding passes, no flares were actually ejected when the button was pressed, but the event was still recorded in the aircraft data system by activating an event switch. The treatment decision for each experimental unit was revealed after the qualification pass.

2.4.3 Results to date

One experimental unit was qualified in 1991, and 14 were qualified in 1993, giving a total of 8 seed and 7 no seed units. One of the seed units cannot be analyzed because of improper radar operation. Appendix B contains summary information for these cases.

A total of 151 convective cells (87 S and 64 NS) have been identified within the 14 experimental units, and their properties have been computed through analysis of three-dimensional, volume-scan, S-band radar data using cell tracking software. The results indicate that AgI seeding may have increased the maximum cell areas by 25 percent, durations by 14 percent, and rain volumes by 69 percent. Little effect is indicated on maximum cell heights, which may be real or caused by underestimation of the glaciated tops of AgI-treated clouds by the S-band radar. None of the results have strong statistical support. Additionally, within the height range of 7 to 11 kilometers, seeded cells of a given maximum echo top produced more rain volume than unseeded cells of the same height.

Partitioning by cloud base temperature increased the apparent effect of seeding to 71 percent, 33 percent, and 125 percent for cell areas, durations, and rain volumes, respectively, within the warm base (temperature > 16 °C) partition. The apparent effect on maximum cell height is on the order of 6 percent.

The outcome for the 14 experimental units (7 S and 7 NS) for which analysis is possible is consistent with a positive effect of seeding. The natural variability is great, and the results are highly sensitive to removal of the wettest unit from each of the S and NS samples.

The results of cold cloud seeding to date are consistent in most respects with the results that have been published previously for Florida and Texas (Gagin et al., 1986; Rosenfeld and Woodley, 1989; 1993). The Thai sample is still very small. Interested parties must be cautious, therefore, in interpreting the results of the seeding until a larger sample has been obtained.

The Thai cold cloud experiments appear to be on the right track, and the obvious recommendation is that they continue in the context of a Phase 2 of Thailand's AARRP cold cloud seeding effort. The design and operations plan for this effort is addressed later in this report.

2.5 Implications of the Results of the Exploratory Experimentation on the Design of the Cold Cloud Demonstration Project

The design of the cold cloud demonstration project will build on the results of the exploratory studies and experiments. Thai cold clouds are clearly suitable for seeding intervention for the enhancement of rainfall. The design of the exploratory experiments worked extremely well in demonstrating the potential of dynamic seeding concepts in Thailand. As a consequence, the design will serve as the basis for the design of the Phase 2 cold cloud seeding experiment. Therefore, the sample obtained so far can be combined with the sample that will be obtained during the course of the Phase 2 effort.

2.6 General Experimental Guidelines

According to Flueck (1986), the objectives in any experimental effort should be to address an apparently "solvable" problem and to achieve a "believable" solution. The characteristics of a potentially solvable problem include being able to state the problem, assuring that the problem is amenable to quantitative analysis, and ensuring that some useful results will be obtained within the constraints of the available resources. The characteristics of a believable solution depend on the plausibility of the theory or conceptual model that is offered to explain the processes of interest, and on the credibility of the supporting statistical evidence. Based on experience in Thailand, a solvable problem—the production of more rain from cold clouds—has been identified, and addressing it with the proposed experiments should lead to a credible solution.

2.7 The Conceptual Model for the Cold Cloud Seeding Demonstration Project

The dynamic seeding conceptual model as discussed most recently by Rosenfeld and Woodley (1993) will serve as the model for the Thai demonstration experiments. The main departure of the new dynamic seeding model from the "classical" model of the past (Woodley, et al., 1982) is the realization that dynamic seeding can also produce a substantial increase in convective rainfall without a large increase in the maximum height of the seeded entity.

New and old scientific findings from a number of research projects support the steps in the new conceptual chain. These findings have been combined with the new results to synthesize a revised conceptual model for dynamic seeding that in no way contradicts the precepts of the old, but merely builds and expands on them in places where physical insight was lacking previously. Part 1 of appendix B provides a complete discussion of the conceptual model that is guiding the Thai experiments.

2.8 Specification of the Design Variables

2.8.1 Experimental unit

The experimental unit will consist of the convective cells that receive real (i.e., AgI flares) or simulated treatment within a circle having a radius of 25 kilometers and centered at the location of the convective cell which qualified for the first treatment. This unit will be advected with the mean speed and direction of the precipitation echoes in its vicinity. The unit will encompass nearly 2,000 square kilometers, which is about the largest area that can be covered effectively with one seeder aircraft.

The selection and termination of the experimental unit will be based upon the following requirements:

1. A preliminary sampling pass shall establish that convective cells in the area contain maximum (1-second values) liquid water contents of at least 1.0 gram per cubic meter and maximum (1-second values) updrafts of at least 1,000 feet per minute (i.e., ≥ 5 meters per second), as determined from real-time readouts aboard the aircraft.

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2. No cloud or cell within the experimental unit at the time of initial treatment shall have a top reaching above 10 kilometers (above ground level).

3. At least some of the subject cells shall have top temperatures of -10 °C or colder.

4. At the time of selection, the center of the experimental unit shall be located at least 40 kilometers from cumulonimbus clouds displaying radar reflectivities of 50 dBZ or greater in the vicinity.

5. Treatment of clouds within the experimental unit is to be terminated if: a) more than 1 hour has elapsed since the last seeding *and* if echoes are no longer contained within its boundaries, and/or b) the experimental unit moves beyond 159 kilometers from the radar, and/or c) the monitoring S-band radar has had an operational failure.

Note that a moving or "floating" experimental unit has been chosen for the demonstration project instead of a unit area that is fixed to the ground. This decision is based on the tremendous variability of suitable, Thai, cold convective clouds that might exist in one area on one day and in another area the next. A fixed-area design would, therefore, not allow for as many seeding opportunities as those provided by a floating area that is tied, not to fixed geography, but to the locations of suitable clouds.

2.8.2 Treatment units

In this design, the treatment units are the convective towers that correspond to the convective cells within the experimental unit and meet the SLWC (supercooled liquid water content) and updraft seeding criteria. The cell receives the treatment, and any effect of seeding should be manifested first in the treatment unit (the cell) and later in the overall experimental unit.

2.8.3 The project study area

Experimental units will be qualified during the cold cloud demonstration project over the area shown on figure 2.1 that is within 159 kilometers of the Omkoi radar in northwest Thailand. The experimental territory excludes all areas in Burma, plus an area of 25-kilometer radius centered on the radar site at Omkoi. This latter region is a "dead zone," in which the radar has difficulty seeing the tops of tall (i.e., > 12 kilometers) echoes during its regular volume scan.

2.8.4 Randomization

The randomized seeding instructions for the demonstration project will be prepared by statisticians with the AARRP. Care will be taken to avoid long runs of the same treatment decision in preparing the randomization.

2.8.5 Type of nucleant and means of delivery

The nucleant to be used in this experiment will be 20-gram AgI flares having the EJ-20 formulation and manufactured by Atmospherics Inc., in Fresno, California, U.S. This flare is complexed with chlorinated hydrophilic material that allows it to nucleate at a faster rate than the modified TB-1 formulation that has been used in Texas. According to tests at the

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Cloud Simulation and Aerosol Laboratory at Colorado State University (fig. 2.2), the EJ-20 and the modified TB-1 flares produce about 3×10^{14} and 8×10^{14} ice crystals per gram of AgI, respectively, at -10 °C. Both flares yield about 10^{13} ice crystals per gram of AgI at -5 °C.

The EJ-20 flares will be ejected in Thailand at the seeding flight altitude (normally 21,500 feet) from the project AeroCommander 690B turbo-prop aircraft. Drop temperature should be $\leq$ -7 °C. When ejected at seeding altitude, each flare normally burns for at least 50 seconds and falls more than 1.5 kilometers in still air. The fall distance obviously will not be as great in strong updrafts. The seeder aircraft will carry a maximum of 200 20-gram flares on each flight.

Sax et al. (1979) showed that on-top seeding with AgI flares produces glaciation along the lines required by the conceptual model. What constitutes intensive seeding has evolved over the years. In experiments over the Caribbean in 1965 and 1967, some tropical clouds received up to 34 kilograms of AgI. In Florida, the amount of AgI per cloud had dropped to 0.5 to 1.0 kilogram, and in Texas the amount was generally less than 0.5 kilogram.

In the Thai experiments to date, the average flare expenditure per cloud pass has been 5 flares, or 100 grams of AgI. This amount will likely be the seeding rate during the demonstration project.

Distribution of AgI, and not its total amount, appears to be the most important consideration in conducting on-top seeding. An amount of AgI has not been specified in the conceptual model for this reason. The duration of seeding and the amount of nucleant that is expended in each experimental unit will be unlimited. Seeding will continue as long as cloud conditions are suitable.

2.9 Experimental Procedures

2.9.1 Forecasting procedures

Implementation of forecasting procedures is a design element that is common to all cloud seeding programs. Forecasting is done to eliminate unacceptable days in advance so that precious resources are not wasted on unsuitable weather conditions. Forecasting will be an important component of the Thai demonstration project, as is obvious from the forecasting procedures to be implemented in the efforts described in "Volume 3 — Demonstration Project Operations Plan." The output of simple cloud models that have been calibrated previously by comparison with observations is vital to the forecast. How this has been done for Thailand is described in appendix C.

2.9.2 Flight procedures

The flight and seeding procedures to be implemented in the Thai demonstration project will be identical to those that were executed in the exploratory experiments described in appendix B and in the Operations Plan that is presented in Volume 3 of this Final Report. The same procedures will be applied to both seeded and non-seeded experimental units, except seeding will be simulated in those units that have randomly been assigned the NS decision.

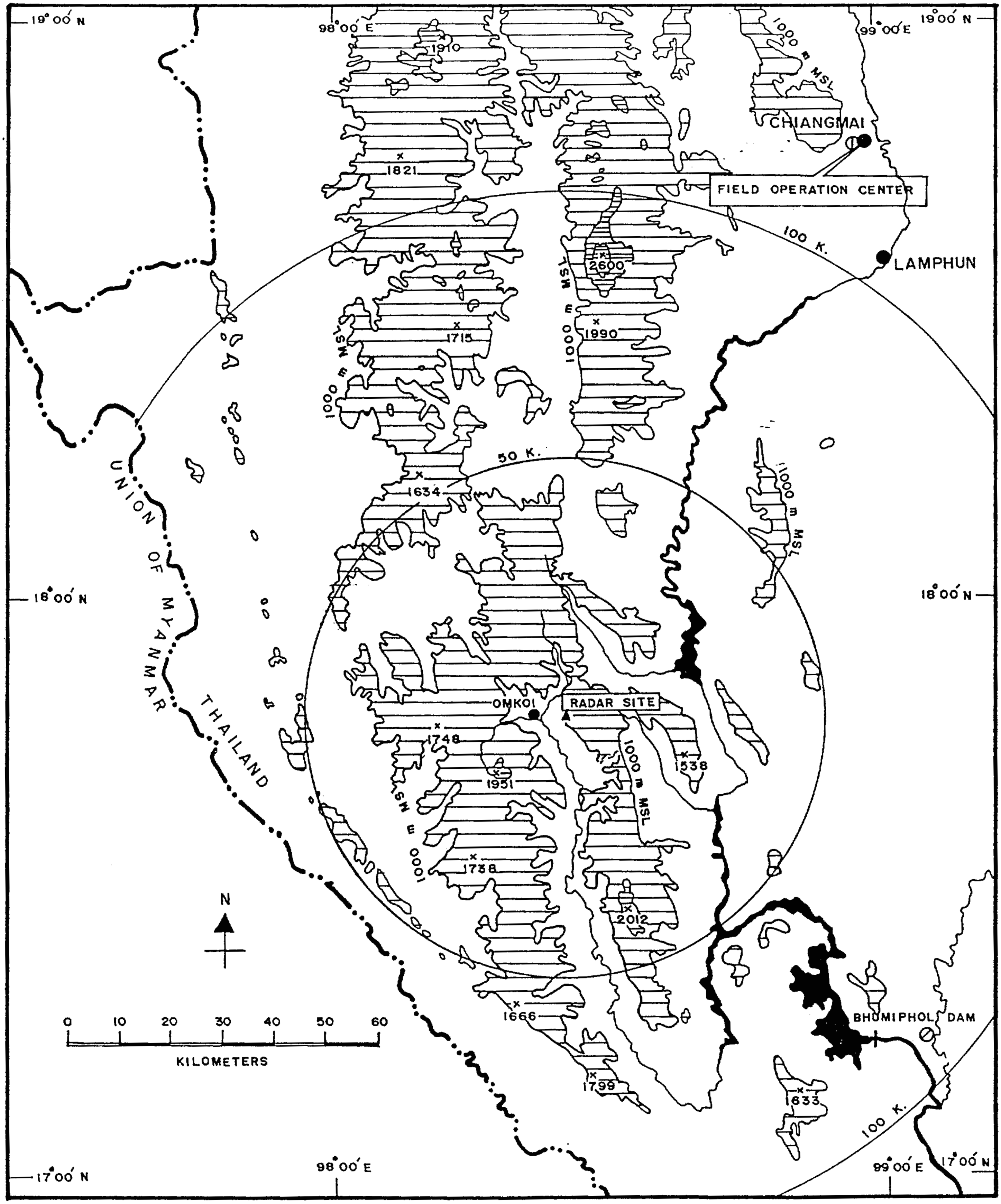

Figure 2.1. - Map showing AARRP project area in northern Thailand.

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Colorado State University
Cloud Simulation and Aerosol Laboratory

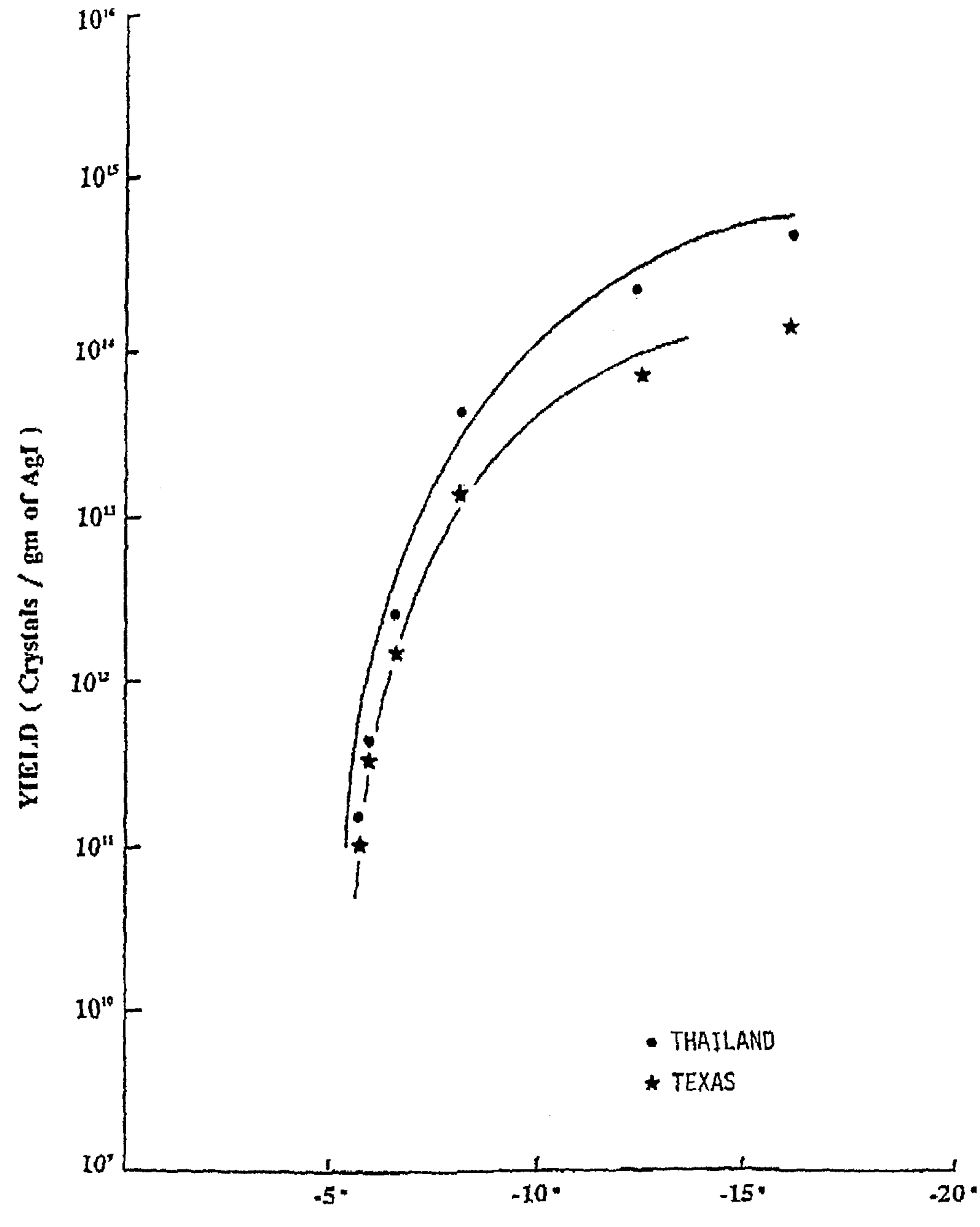

Figure 2.2. - The yield in ice crystals per gram of AgI as a function of temperature for two pyrotechnic formulations by Atmospherics, Inc. of Fresno, California. The top curve corresponds to the EJ-20 flare that is used in Thailand. The bottom curve corresponds to the modified TB-1 flare that is used in Texas. The tests were performed in the Cloud Simulation and Aerosol Laboratory at Colorado State University in Ft. Collins, Colorado.

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2.10 Projected Duration of the Demonstration Project

The criterion for success of the demonstration project will be plausible, physically based, and statistically significant indications of increased rainfall from the convective cells that received AgI treatment *and* from the experimental units that contained the AgI-treated cells. Based on the results of the exploratory experiment, the criterion for success is expected to be satisfied first for the convective cells and then for the experimental units that contain the cells. The reasons for this expectation are twofold. First, the effect of treatment will be larger for the cells than for the experimental units because the cells receive the AgI. Second, the cell sample size will be larger than the sample of experimental units because more than one treated (i.e., AgI or simulated AgI) cell is obtained within each experimental unit.

These expectations are supported and quantified by calculating the number of random cases (i.e., experimental units) and cells that will be required in Thailand to detect a given seeding effect at the 5-percent significance level at a given power. The results are based on 2,000 permutations or rerandomizations of the ratios of S to NS rainfalls. For comparison purposes, the same calculations were run for data obtained in Texas. The computations were made by Dr. Ronit Nirel of the Department of Statistics at the Hebrew University of Jerusalem.

The required sample size, N, is calculated according to the following relationship:

$$N = (Z_\alpha + Z_\beta)^2 \text{ x } (\sigma^2/\delta^2)$$

where Z_α is the (1 - α) cumulative fraction of a standard normal distribution; Z_β is the (1 - β) percentile of a standard normal distribution; α is the significance level of a one-sided test that excludes a priori a negative seeding effect ($\alpha = 0.05$); β is the probability of concluding that no effect of seeding exists when an effect actually exists, and 1-β is the power of the experiment, which is defined as the chance or probability of detecting an effect of seeding when an effect of seeding actually exists; σ^2 is the variance of the *SR* (single ratio) of S (seed) to NS (no seed); δ is the seeding effect (*SR*-1); and *SE*(*SR*) is the standard error of the estimate of *SR*.

Note that a large variance of *SR* and a small seeding effect means a large *N*. The calculations of *N* for cells and experimental units in Thailand and in Texas are provided in tables 2.1 and 2.2, respectively.

A power of 0.80 was used in these calculations because of the small sample size from which to calculate *SR* and its resulting high variance. The variance will likely decrease as the sample is increased during the demonstration project, and project duration will be re-estimated using a power of 0.90. This method should provide a better estimate of the required project duration, one that should be of lesser duration than that projected currently.

Care should be exercised in interpreting these calculations. However, reaching a definitive conclusion for individual cells in both Texas and Thailand should be relatively easy because the observed *DELTA* is > 1.0 in Texas and also in Thailand for the warm cloud base (i.e., > 16 °C) partition. Thus, one might reasonably expect to reach statistical significance for the Thai cell experiments in only one or two more seasons of experimentation, mainly for cells with base temperatures > 16 °C.

The situation for the experimental units is more complicated because of the small Texas and Thailand samples. In Thailand, the current best estimate of the seeding effect on the experimental units is 0.66 (i.e., *SR* = 1.66). Examining the appropriate portion of table 2.1, one can see that detecting this seeding effect will take about 125 randomly-selected experimental units at a one-sided significance level of 5 percent at a power of 0.80. Obtaining such a sample during the five years that have been allotted to Phase 2 should be possible. This possibility assumes, of course, that the current best estimate of the seeding effect for the unit is representative of the true seeding effect.

In Texas, the apparent seeding effect on the experimental units by 150 minutes after initial seeding is on the order of 0.27 (i.e., *SR* = 1.27). Thus, the calculations presented in table 2 suggest that as many as 400 random cases could be needed to detect this effect at a 5-percent significance level at a power of 0.80. If this set of computations is representative of the real situation in Texas, obtaining such a sample size using a raw "brute force" approach might never be practical without the benefit of covariates.

Fortunately, the use of covariates can reduce the number of cases needed to establish an effect of seeding. It is well-known, for example, that a covariate that is correlated with the rain volume in the experimental unit by coefficient R will reduce the required number of random cases N to $N(R)$ according to:

$$N(R) = (1\text{-}R^2)\ N(SR)$$

To illustrate how this formula works, assume that an identified variable is correlated with rain volume in the experimental unit by 0.70 (i.e., $R = 0.70$). Then, the 125 cases that were cited above as necessary to resolve a seeding effect in Thailand of 0.66 decreases to about 64 cases. Therefore, identifying covariates in cloud seeding experiments has great benefits. This technique should be a major area of research during the Thai demonstration experiment.

2.11 Evaluation

2.11.1 Evaluation parameters

The evaluation of the results of the demonstration project will be similar to that described in appendix B of this report. The focus will be on the individual cells and on the experimental unit that contains the cells. The specific evaluation parameters for the cell analyses will include S versus NS ratios of mean cell heights, reflectivities, areas, durations, rain-volume fluxes, lifetime rain volumes, and the number of cell mergers. For evaluation of the experimental units, the parameters will include ratios of mean "focused-area" and unit echo areas, durations, and rainfalls. The focused-area analysis is explained later in this section. All analyses will proceed with and without partitioning by cloud-base temperature.

2.11.2 Approach

The results cannot depend on the approach to the analyses, as was the case for the analysis of the exploratory experiment. Further, seeding effects should be indicated in most of the analyses; they should be consistent with the conceptual model, and some of the results should be statistically significant after accounting for some of the natural variability. In essence, therefore, the analysis process must not be a mathematical exercise. All results must be plausible, reasonable, and physically consistent if they are to be believed.

Table 2.1. - Estimation of the number of cases (N) that will be required for the cold cloud seeding demonstration project to reach a statistical significance level of 0.05 at a power of 0.80 as a function of possible seeding effect. Top: for individual cells. Bottom: for experimental units.

RVOL for individual cells
(α = 0.05 and 1 - β = 0.80)
Var(SR) = 21.0 and SE(SR) = 1.22

DELTA	0.5	1.0	1.5	2.0	2.5
N	659	165	73	32	21

Note: A total of 151 cells have been obtained from 14 random cases in Thailand to date with δ = 0.69. The sample of cells, obtained from 10 random cases having cloud bases > 16 °C, is 108. The estimated δ for that sample is 1.25.

RVOL for random cases for 150 minutes after initial treatment
(α = 0.05 and 1 - β = 0.80)
Var(SR) = 13.5 and SE(SR) = 0.94

DELTA	0.3	0.4	0.5	0.6	0.7
N	927	522	334	148	109

Note: The above estimates of N are based on only 14 random cases and may, therefore, not be representative. The current δ of 0.66 is not yet a strong indication for the real magnitude of the effect in view of the high Var(SR).

Table 2.2. - Estimation of the number of cases (N) that will be required in Texas to reach a statistical significance level of 0.05 at a power of 0.80 as a function of possible seeding effect. Top: for individual cells. Bottom: for experimental units.

RVOL for individual cells
(α = 0.05 and 1 - β = 0.80)
Var(SR) = 7.25 and SE(SR) = 1.22

DELTA	0.5	1.0	1.5	2.0	2.5
N	179	45	20	11	7

Note: A total of 183 cells have been obtained from 24 random cases in Texas to date with δ = 1.30. The sample of cells, obtained from 10 random cases having cloud bases > 16 °C, is 85, and the δ for that sample is 1.85.

RVOL for random cases for 150 minutes after initial treatment
(α = 0.05 and 1 - β = 0.80)
Var(SR) = 5.50 and SE(SR) = 0.40

DELTA	0.1	0.2	0.3	0.4	0.5
N	3400	850	378	213	136

Note: The above estimates of N are based on a random sample of 34 random cases and may, therefore, not yet be representative. The current δ is 0.27.

2.11.3 Accounting for natural biases

2.11.3.1 The identification of control cells

Any analysis of seeding effect must include an accounting for at least some of the natural variability. Our first possible approach will be that pioneered by Gagin et al. (1986) and refined by Rosenfeld and Woodley (1989), which made use of "control" cells in the environments of the AgI-treated and simulated AgI-treated cells. This approach was not feasible, however, for the experimental units obtained in Texas in 1989 and 1990, because too few control cells could be identified on some days of experimentation. The use of this approach in Thailand, therefore, will depend on whether a sufficient number of control cells can be identified on each day of experimentation. This approach is described in detail below because it *may* be used in Thailand.

If the properties of control cells, as defined momentarily, were perfectly correlated with the cells within a NS experimental unit, then the seeding effect could be determined by the *DR* (double ratio):

$$DR = SR/CR$$

where *SR* (single ratio) is the simple apparent seeding effect, given by:

$$SR = (\ )T_{AgI}/(\ )T_{sim}$$

and *CR* (control ratio) is the bias caused by the natural variability, given by:

$$CR = (\ )C_{AgI}/(\ )C_{sim}$$

where the values in parentheses can be the mean of any of the lifetime properties of the cells; *T* stands for treated cells, *C* for control cells; *AgI* denotes the cells in which AgI seeding took place, and "*sim*" denotes the cells in which seeding was simulated.

In defining the cells to be used as controls, Rosenfeld and Woodley (1989) had to consider several factors. First, the prospective cells had to conform as much as possible to the selection criteria of the actual experimental cells that received S or NS (simulated) treatment. Second, the control cells had to be separated from the S and NS cells by a minimum distance to ensure that the experimental cells did not contaminate those cells, which were to be used as controls. Third, because of range biases in cell measurements that can result from the characteristics of the measurement radar, each set of control cells had to be located as far from the radar as the experimental cells that resided within each experimental unit.

The initial criteria for the selection of the control cells in the AARRP will be the following:

1. The prospective cell must be tracked for at least two radar scans,

2. The cell is no more than 125 kilometers from the radar at the time of its birth,

3. The prospective cell is never within 35 kilometers of any treated cell,

4. The height of the prospective control cell must be at least 6.5 kilometers on the second radar scan, and it must be taller on the second scan than on the first, but not more than 10 kilometers,

5. The reflectivity of the prospective cell must be greater on the second radar scan than on the first,

6. The prospective control cells must reside in the 60-kilometer-wide annulus that is centered on the mean range of the treated cells for which the controls are being selected.

The last criterion is best understood by reference to figure 2.3, in which the treated cells, the environmental cells, and the control cells are plotted. Note that the three treated cells (either S or NS) are defined to have a 25-kilometer region of effect around them, and that the environmental cells are defined as those cells which did not receive either S or NS treatment that live in this region of effect. The cells which are to be used as controls are depicted schematically in the 60-kilometer-wide annulus. The center of this annulus is at the mean range of the treated cells from the radar. To be consistent with criterion No. 3, the annular region in which the control cells can be selected must end at least 35 kilometers from the treated cells. In essence, therefore, at least a 10-kilometer buffer exists between the area of effect and the region that contains the control cells.

Before the control cells can be used for evaluation of the Thai cell experiments, the control values corresponding to each of the experimental units must be weighted as a function of the number of treated cells in that unit. If this weighting is not done, the overall control value for the S and NS units will be dominated by the unit that has the most control cells. Thus, the control cells have the same weight and influence as the treated cells (either S or NS) that they are meant to represent.

This approach worked quite well initially in Texas (Rosenfeld and Woodley, 1989), where the control cells were positively correlated on a unit-by-unit basis with the corresponding properties of the cells that were randomly selected for treatment but did not receive AgI (i.e., the NS cells). The correlation was found to be strongest for R_{vol} and A_{max} and weakest for Z_{max}. The R_{vol} correlations indicate that between about 30 and 60 percent of the rainfall variability of the NS cells in Texas can be accounted for by the control cells. In cloud seeding studies, this level of performance is rather good for one control variable. This approach is expected to work as well in the AARRP *if it proves possible to identify many control cells for each experimental unit.*

2.11.3.2 Linear modeling of the unit rainfall

A number of additional ways exist to address the natural rainfall variability in a randomized cloud seeding experiment. One possibility is to follow the example of Flueck et al. (1986) and use a guided exploratory approach to linearly modeling the unit rainfall in the Thai program. This process relies upon an initial crude conceptual model of Thai rainfall and repeated interaction between the scientist and the computer-generated summary statistics to systematically build a predictive statistical linear model of the unit rainfall and the potential treatment effects.

The linear modeling will attempt to account for the effects of natural atmospheric processes on the rainfall response variable (y), as well as the effects of the treatment. In statistical terms, a statistical linear predictive model will be defined and fit to the unit area rainfall:

$$y^* = b_o + b_1x_1 + b_2x_2 + ... + b_kx_k$$

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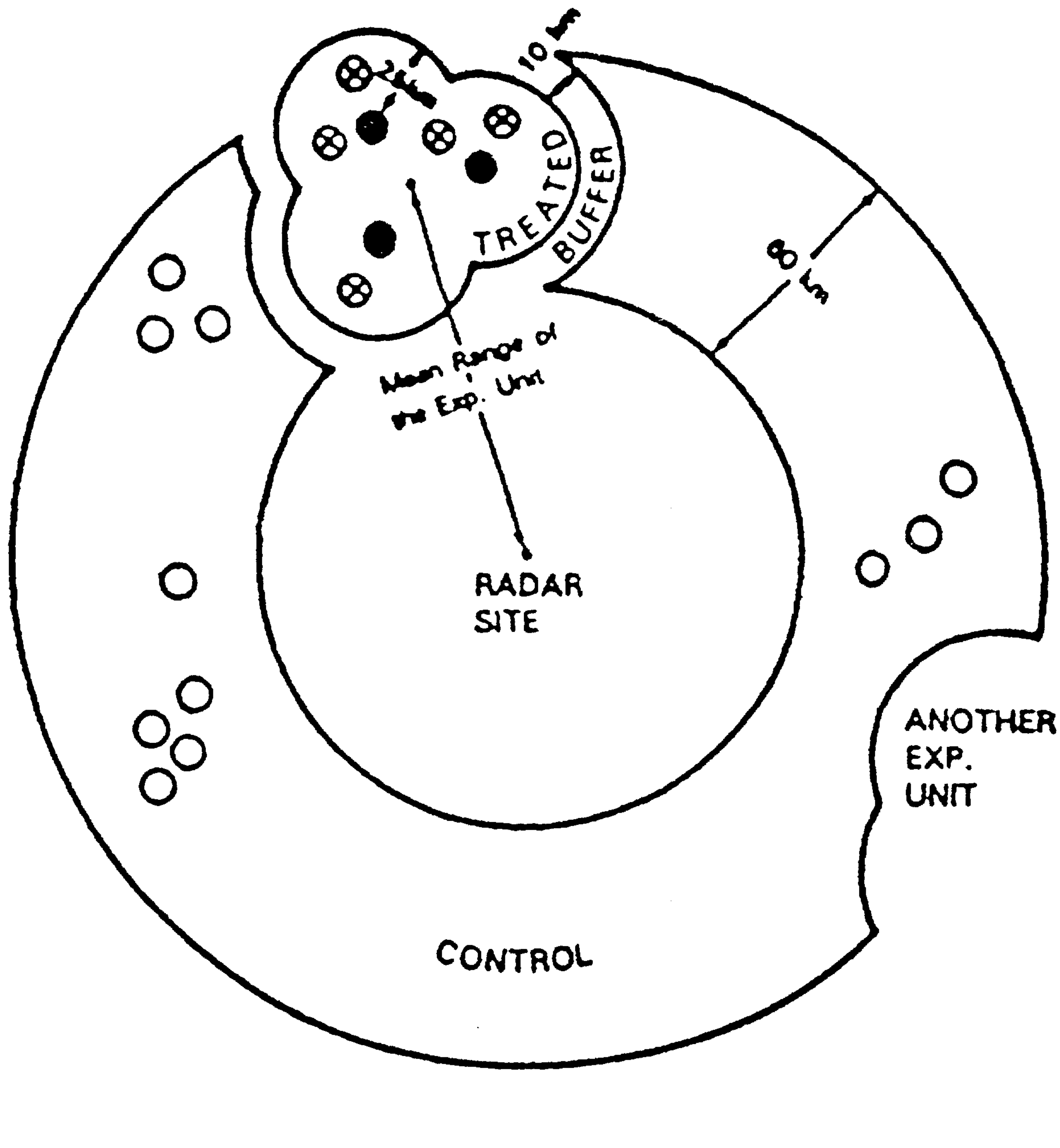

Figure 2.3. - The partition of the area into control area and seeding influenced area, and the location of the three types of cells (treated: solid circles; environmental: circles with crosses; and control: open circles) relative to the radar location and the treatment coordinates.

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where

y^* = the predicted unit area rainfall variable

x_1 = the treatment (seeding) factor of interest, and

x_i (i = 2, ..., k) = the (k-1) predictor or concomitant variables.

The x_i variable is different from the others because it is an index variable that signifies the presence or absence of the randomized treatment and hence is termed a factor. This factor will be examined for evidence of treatment (i.e., seeding effect). The other variables are concomitant or predictor variables and are present to account for some of the natural variability in the rainfall response variable (y).

The concomitant or predictor variables to be selected for inclusion in the linear model will probably come from the categories of meteorological processes that likely influence rainfall in Thailand. These categories include:

1. Mesoscale prewetness as estimated by radar-measured rainfall rates in the target or adjacent areas prior to the time of first unit treatment,

2. Thermodynamic structure of the atmosphere as measured by the GPCM (Great Plains Cumulus Model) and/or by standard stability indices,

3. Kinematic structure of the atmosphere as represented by wind speed and/or direction and vertical wind shear.

4. Cloud-scale suitability of the day as indicated by convection having substantial SLWC (i.e., > 1.0 gram per cubic meter) and strong updrafts (i.e., > 5 meters per second), and

5. Synoptic scale rainfall as estimated by radar reflectivity for large areas that are some distances from the target and hence presumably unaffected by treatment.

The candidate predictor variables to be selected from the above five categories will be identified during the course of the project in consultation with Thai project scientists.

2.11.4 Statistical significance tests

The probability that the results of the demonstration project are caused by chance will be calculated by a refinement of the Monte Carlo rerandomization test (Gabriel and Feder, 1969). This calculation will be done in the following steps for the experimental units:

1. A randomization reallocation of the experimental random cases to S and NS will be made. If the randomization is constrained to disallow runs of the same treatment decision within each block, the rerandomization draws will be similarly constrained.

2. The *SR* between all the S and NS randomized cases will be calculated.

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3. Steps 1 and 2 will be repeated for all of the permutations that are possible after following the protocol described above, and a sorted vector of the SR's obtained in the permutations will be produced.

4. The fraction (*P*, in percent) of the randomly obtained *SR*'s which are larger than the observed one in the real experimental allocation is the chance that the experimental result is caused by the natural variability. This chance is referred to as the "significance level."

2.11.5 Seed versus no seed comparisons

Several analyses will be pursued in the S versus NS cell comparisons. The first will be comparison of means, SR, and DR, if appropriate, for the various cell properties as a function of treatment decision. This analysis will be done for the "long track" calculations, and the results will be stratified by the number of flares and time of treatment. In addition, plots of mean cell properties versus time for the S and NS samples will be constructed. Finally, time-height reflectivity plots will be composited for the S and NS cases. The time of the qualification pass will be used as the "0" time reference in all time plots. All analyses will be done for both approaches.

Once the cell comparisons have been completed, analyses for seeding effects beyond the scale of individual cells will be made. The first will look at the merger of cells to see whether merger is more prevalent in S cells than in NS cells. In Texas, the S cells merged more often than the NS cells (Rosenfeld and Woodley, 1989; 1993) in agreement with the conceptual model. The same result is expected in Thailand.

The next analysis will be the "focused area" approach that involves calculation of cell properties for various radii around each treatment position as a function of time. In Texas, the effect of seeding appears to begin on the scale of the individual cell and spread outward with time (Rosenfeld and Woodley, 1989; 1993). Using this "focused area" approach, which is discussed extensively by Rosenfeld and Woodley (1993), it will be possible to determine whether this effect exists in Thailand.

Finally, the experimental units containing all of the cells, including those that did not receive either AgI or simulated AgI treatment, will be examined for seeding effects. Each experimental unit covers about 2,000 square kilometers, and documenting seeding effects on this scale will be more difficult, as was shown in the section dealing with the duration of the experiments.

3. DESIGN OF THE THAI WARM CLOUD RAINMAKING DEMONSTRATION PROJECT

3.1 Statement of the Problem

The scientific question to be addressed is whether the seeding of warm convective clouds with hygroscopic particles over a target area of 900 square kilometers can produce substantial and statistically significant increases in rainfall over that area. An additional scientific question that must be addressed is whether this increase in rainfall over the target area, if any, is in fact an increase in rainfall or a redistribution of the rainfall that would have occurred in the absence of seeding. The larger socioeconomic question is whether the proposed warm cloud seeding methodology can and should be used to assist Thailand in managing its water resources.

3.2 Principles of Warm Cloud Seeding for Rain Enhancement

The evolution of rain in warm convective clouds and the amount of rain falling to the ground involves a number of complex, interacting microphysical and dynamic mechanisms. The process starts with the condensation of water vapor on CCN (cloud condensation nuclei) to form the cloud droplet spectrum. Growth of the cloud droplets continues by condensation and stochastic coalescence between pairs of small droplets to form precipitation embryos (autoconversion). More rapid growth then occurs through the collision-coalescence process (accretion) to form rain drops which are capable of falling against the updraft. Break-up of rain drops may occur as a result of a collision with another drop or because of aerodynamic instability of the rain drop. Some evaporation of the rain drops occurs because of entrainment of dry air in the cloud and as they fall into the drier subcloud layer. It is important to note that the time required for the rain evolution processes to operate takes place in a cloud whose lifetime is governed by thermodynamic and dynamic processes such as entrainment, water loading, and buoyancy.

The efficiency of these rain evolution mechanisms depends on many factors, including the size and number of CCN, the cloud base temperature, the cloud updraft velocity, the size of the cloud, and, in general, the time available for these mechanisms to act. The principles of warm cloud seeding, principally hygroscopic particle seeding, for rain enhancement are rooted in these efficiency factors. There are four main approaches to increasing precipitation from warm convective clouds through hygroscopic particle seeding:

1. Seeding with very small hygroscopic particles, about 0.1 to 1.0 micrometer in radius, in the subcloud layer to modify the CCN upon which the cloud droplet spectrum first forms, by making it more maritime in character and thereby improving the inherent efficiency of the condensation and autoconversion processes.

2. Seeding the cloud with small hygroscopic particles, about 5 to 10 micrometers in radius, to accelerate the natural autoconversion process of the cloud.

3. Seeding the cloud with large hygroscopic particles, about 50 to 100 micrometers in radius, to bypass the autoconversion process and initiate the collision-coalescence process earlier in the life of the cloud.

4. Seeding the cloud with a combination of exothermic and endothermic hygroscopic particles at different stages of cloud development to: a) invigorate the cloud's updraft, thereby initiating warm convective clouds and/or stimulating their growth, and then b) increase the coalescence rate of conversion of cloud water to precipitation particles with respect to the rate of loss of cloud water to other sinks and, at the same time, invigorate cloud downdrafts to help the hydrometeors reach the ground.

The first three approaches are designed to produce microphysical effects that will improve the efficiency of the rain evolution mechanisms and decrease the time required to initiate the precipitation process; the fourth approach is designed to produce a combination of microphysical and dynamic effects to maximize the rainfall falling at a specific location on the ground. The reader is referred to the WMO Report of the Meeting of Experts on Warm Cloud Modification, Kuala Lumpur, March 18-24, 1981 (WMO, 1981b), for a more complete discussion of this subject.

3.3 Summary of Results of Relevance to Thailand

Since about 1955, experiments and projects designed to increase precipitation through hygroscopic particle seeding have been conducted, involving both ground and airborne seeding methods. Only the most relevant scientific studies are mentioned here; the reader is referred to Cotton (1982) for a more complete discussion of this subject.

Biswas and Dennis (1971) reported that the seeding below one end of a line of stratocumulus clouds with 350 pounds of sodium chloride resulted in a shower, and that no rain fell from any other clouds within 50 miles of the seeded cloud. In subsequent calculations (Biswas and Dennis, 1972), they postulated that a chain reaction process stimulated by the salt seeding was likely involved in the evolution of precipitation.

A long series of hygroscopic particle seeding experiments on warm convective clouds has been carried out in India (see, for example, Biswas et al., 1967; Kapoor et al., 1976; and Murty, 1989). Murty (1989) reported the results of an 11-year randomized crossover experiment in which warm convective clouds were seeded at cloud base with sodium chloride particles 10 micrometers in size. The seeding on days when the experimental area was covered by clouds (area seeding days) was about 10 to 30 kilograms per kilometer, and the seeding on days when the experimental area had only a few clouds (target-control days) was 700 to 1000 kilograms per cloud. For 80 pairs of area seeding days, he reported an increase in rainfall of 24 percent at a 4-percent significance level. For 62 pairs of target-control days, he reported a decrease in rainfall of 35 percent, which was not statistically significant.

Experiments to increase precipitation from warm cloud base convective clouds using hygroscopic flares are being conducted in South Africa (Mather and Terblanche, 1992). In these experiments, hygroscopic flares are burned in the subcloud layer which introduce about 10^{11} particles per flare greater than 1 micrometer in diameter. The particles are a mixture of sodium chloride, potassium chloride, lithium carbonate, and magnesium oxide. Mather and Terblanche (1992) report that cloud physics measurements taken during seeding trials with the hygroscopic flares support the hypothesis that the seeding is initiating, or at least enhancing, the coalescence process. Statistical analysis of the first year of a multi-year hygroscopic flare seeding experiment in South Africa (Steffens, 1992) indicates that rainfall from seeded clouds is greater than that in non-seeded clouds, but has no statistical significance.

Extensive cloud seeding operational projects using hygroscopic particle seeding have and are continuing to be carried out in Thailand, Malaysia, Indonesia, and the Philippines [see RRRDI (1988) for a complete discussion of these projects]. Organizations carrying out these projects are encouraged by their results; however, these projects have not received the statistical and physical evaluation that is required to make the results acceptable to the scientific community.

The general consensus of the scientific community (WMO, 1981b) is that no scientific proof exists of the efficacy of procedures to modify warm clouds so as to increase or redistribute precipitation; however, the results of past warm cloud seeding projects are encouraging, and more study and resource commitment to warm cloud modification is warranted.

3.4 Summary of Warm Cloud Seeding Model Experiments

3.4.1 Introduction

A numerical cloud model that is capable of simulating cloud and precipitation development under natural and seeded conditions was used in the search for a viable warm cloud seeding strategy. The numerical cloud model provided an inexpensive means of screening numerous candidate warm cloud seeding strategies to identify those that are most promising scientifically (WMO, 1981a). The one-and-one-half-dimensional, time dependent, detailed microphysical model originally developed by Silverman and Glass (1973), as extended by Nelson (1979) to include ice processes, and further updated by Silverman to include ice multiplication processes and a variety of hygroscopic chemical seeding options (HAMOD), was used to test the relative effectiveness of a wide range of seeding scenarios.

Of the most scientifically promising seeding strategies found in these model experiments, the one that best meets the logistical and economic feasibility requirements is recommended for incorporation in the design of the warm cloud seeding demonstration project. A complete description of the model, the model experiments, and the experimental results is given in appendix D.

3.4.2 Results to date

The key results of the numerical model experiments are summarized as follows:

1. The CCN spectrum upon which warm and cold clouds develop in the project area has a strong influence on the production of natural rainfall. As the CCN spectra change from one primarily maritime in character (low number concentration and relatively high numbers in large nuclei sizes) to one that is more continental in character (high number concentration and very few in large nuclei sizes), the amount of natural rain produced decreases markedly. The decrease is greater in warm clouds, which depend solely on the condensation-coalescence process for precipitation development, than in cold clouds, which include precipitation development through ice processes as well. The burning of rice fields and forest areas in the project area produces a smoke containing nuclei which, from evidence in other projects, suggests that the natural CCN spectrum is probably being made more continental in character.

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2. Hygroscopic particle seeding leads to increased precipitation by producing microphysical effects that improve the precipitation efficiency of warm and cold convective clouds. No dynamic effects occur as a result of the exothermic or endothermic nature of the hygroscopic chemicals.

3. Of the four hygroscopic chemicals investigated, seeding with dry $CaCl_2$ (calcium chloride) particles produces the largest seed/no-seed ratios.

4. For clouds with limited lifetime, the largest seed/no-seed ratios are achieved with 50-micrometer-radius $CaCl_2$ particles for both cloud base and near cloud top seeding. For clouds of longer duration, the best results are achieved with smaller radius $CaCl_2$ particles: 30-micrometer-radius particles for cloud base seeding and 10-micrometer-radius particles or less for cloud top seeding. Seeding with readily purchased size distributions of $CaCl_2$ results in smaller seed/no-seed ratios than seeding with monodisperse particles; nevertheless, observable seed/no-seed ratios are achieved.

5. The seed/no-seed ratios for $CaCl_2$ seeding increase with increasing seeding concentration or dosage; however, logistical considerations will place an upper limit on what is possible.

6. Cloud base seeding with $CaCl_2$ produces larger seed/no-seed ratios than near cloud top seeding.

7. Seeding with $CaCl_2$ particles is most effective when conducted early in the life of a growing cloud (about 5 minutes after cloud formation), when the precipitation initiation process can still be influenced.

8. Hygroscopic particle seeding can increase precipitation from both warm and cold clouds.

9. Hygroscopic flares can increase precipitation from both warm and cold clouds, but their effectiveness is highly dependent on the existing natural nuclei spectrum.

10. Warm cloud seeding with hygroscopic particles can produce seeding effects that result in measurable increases in precipitation.

3.5 Implications of Model Seeding Results on the Design of the Warm Cloud Seeding Demonstration Project

Combining the analyses of scientific feasibility (see appendix D) with considerations of economic and logistical practicability leads to the following recommendations for the warm cloud seeding demonstration project:

3.5.1 Seeding agent

Polydisperse $CaCl_2$ particles as purchased is recommended as the seeding agent. Storage and handling procedures that prevent the degradation of the spectra should be instituted. Monodisperse distributions are not recommended because the cost of acquiring and maintaining such distributions is prohibitive.

Hygroscopic flares are not recommended at this time, despite their very promising results, because: a) their true effectiveness cannot be estimated until data on the nature and variability of the natural nuclei spectrum in the target area are obtained, and b) the hygroscopic flare seeding operation at very low altitudes in the subcloud layer probably cannot be accomplished in the mountainous terrain of the target area without considerable practice, if at all. Nevertheless, future implementation of this approach should be actively explored because it is potentially more efficient and much less expensive. Therefore, the procurement and installation of a ground-based CCN counter at the AARRP radar site is highly recommended so continuous measurements of CCN can be made.

3.5.2 Seeding strategy

Seeding should be conducted as soon as the qualification criteria in the target areas are met without regard to or fear that the clouds will grow above the freezing level. Seeding should be conducted as low in the cloud as possible consistent with good flight safety practices. Seeding should be conducted by two CASA aircraft with appropriate time and/or space separation to maximize the seeding concentration. Considering that the maximum payload of each aircraft is 1200 kilograms, that the aircraft customarily fly at 120 knots, and that the seeding material cannot be dispensed in less than 15 minutes, those factors will result in a seeding concentration of 0.0685 gram per cubic meter.

3.5.3 Additional Studies

The warm cloud seeding findings are based almost exclusively on numerical model experiments which, although consistent with other model studies and field experiments conducted elsewhere, do not yet have the benefit of field verification in the proposed target area. Preliminary confirmation of expected physical effects was planned during the 1993 field season, but could not be pursued because of equipment failure. Therefore, it is recommended that the demonstration project include physical studies and additional model studies to confirm the nature and magnitude of predicted effects on individual warm and cold clouds.

3.6 The Conceptual Model for the Warm Cloud Seeding Demonstration Project

The results of the numerical model seeding experiments support the scientific feasibility of all three approaches that are designed to produce microphysical effects that will improve the efficiency of the rain evolution mechanisms and decrease the time required to initiate the precipitation process. Considering the fact that economic and logistic factors require that the seeding be done with relatively large polydisperse $CaCl_2$ particles, the conceptual model for the warm cloud seeding demonstration project is based on accelerating the coalescence process by bypassing the autoconversion process and initiating the collision-coalescence process earlier in the life of the cloud. It is postulated that by reducing the time required for the precipitation process to evolve with respect to the time available, rain efficiency will increase such that clouds that would not naturally rain will rain, and clouds that would naturally rain will rain more.

3.7 Warm Cloud Seeding Hypotheses

The following four null hypotheses will be tested in the warm cloud seeding demonstration project:

H01: Hygroscopic seeding does not affect the probability that rain will fall somewhere in the target area in the first hour after seeding commences.

H02: Hygroscopic seeding does not alter the mean area covered by rainfall during the experimental unit.

H03: Hygroscopic seeding does not alter the total rainfall volume per experimental unit.

H04: Hygroscopic seeding does not alter the rainfall in the downwind area.

Rejection of the four null hypotheses will signify the following:

H11: Hygroscopic seeding causes rain to fall from clouds that would not otherwise produce rain.

H12: Hygroscopic seeding increases the areal extent or duration of natural rain showers.

H13: Hygroscopic seeding increases the total amount of rainfall per experimental unit.

H14: Hygroscopic seeding-produced increases in experimental unit rainfall either merely redistribute the rainfall that would have fallen naturally or enhance downwind rainfall as well.

3.8 General Experimental Design

The warm cloud seeding demonstration project will be conducted in accordance with a randomized crossover design (appendix E). Two pairs of target areas (fig. 3.1) have been selected: a western pair (TA-W1 and TA-W2), which is suitable for use during the morning hours; and an eastern pair (TA-E1 and TA-E2), which is suitable for use during afternoon hours. Control and downwind areas have been selected for each target pair (appendix E). Thus, more than one experiment can be conducted on any given day, cloud conditions and logistics permitting.

3.9 Specification of Design Variables

3.9.1 Experimental unit

The experimental unit will be the assemblage of all clouds that occur in the target areas during a 3-hour period; sometime during 0900 to 1300 LST for the west target pair and some time during 1300 to 1800 LST for the east target pair.

3.9.2 Treatment units

The treatment units are all clouds within an experimental unit that are actually treated.

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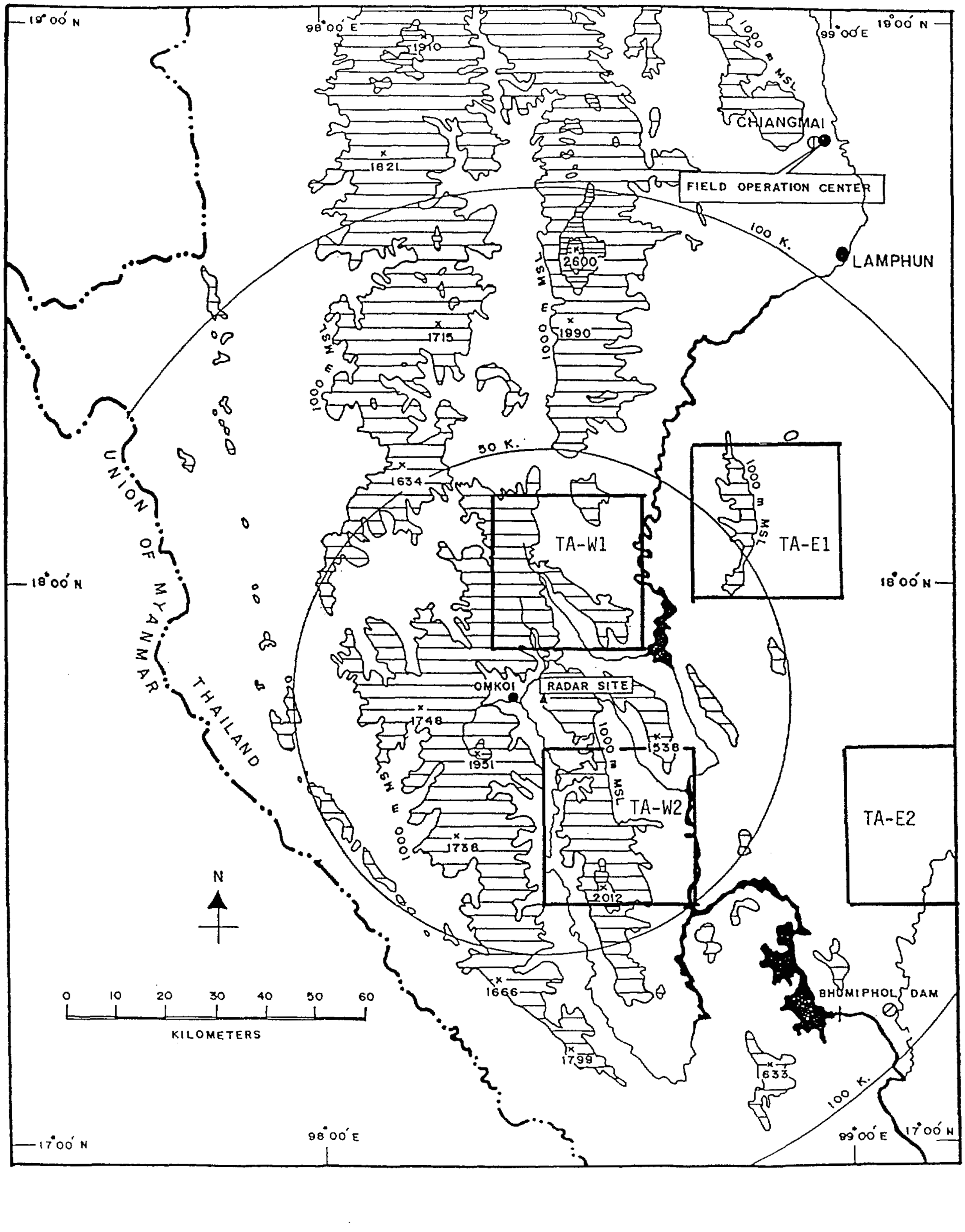

Figure 3.1. - Map of northern Thailand showing the location of the radar and the two pairs of target areas for the warm cloud seeding demonstration project.

3.9.3 Randomization

Morning seeding of the west target pair and afternoon seeding of the east target pair will each be separately controlled by their own sequential lists (envelopes) of experimental unit decisions to seed or not seed the northern target area of the pair (if not treated is drawn, the southern target area of the pair is treated). Block randomization will be used in each case to ensure that each target area in the pair is treated about the same number of times.

3.9.4 Type of nucleant and means of delivery

The nucleant to be used in this experiment will be the exothermic hygroscopic chemical $CaCl_2$. The $CaCl_2$ is acquired from the manufacturer in relatively small-size particles and packaged in 25-kilogram bags. During seeding operations, the bags are slit open just prior to seeding and the contents are poured into a hopper that empties into the airstream below the fuselage of the aircraft.

The aircraft speed during seeding is about 120 knots. The seeding chemicals are dispensed (poured out) from the aircraft at a rate of about 75 kilograms per minute. Thus, the average seeding dosage is about 21 kilograms per kilometer.

The size distribution of the $CaCl_2$ at the time of milling by the manufacturer is generally known; however, this size distribution shifts to larger sizes as a result of clumping during storage and handling in the high humidity environment of Thailand. Because $CaCl_2$ absorbs moisture at very low relative humidity (about 18 percent), great care must be exercised during the storage and handling process to maintain the original size distribution of the particles. Given the relationship of the size distribution of the hygroscopic chemicals to its payload effectiveness (appendix D), it is important to prevent the degradation of size distribution of the hygroscopic chemicals that will be used in the seeding operation.

3.10 Experimental Procedures

The experimental procedures that will be used in the warm cloud demonstration project are discussed in detail in "Volume 3 - Demonstration Project Operations Plan." The two-area or target-control design involves a random choice of either treating or not treating experimental units associated with a specified target area; however, measurements are also obtained from a control area. The analysis of results is based on differences between target area measurements for treated and nontreated experimental units; however, observations in the target area are adjusted on the basis of observations in the control area, thereby accounting for some of the natural variability.

The experimental unit is terminated if more than 60 minutes have elapsed since the end of treatment. The experimental unit can also be terminated by failure of the measurement and/or seeder aircraft and/or the monitoring S-band radar. In addition, the experimental unit can be terminated if the seeding required by the randomization decision cannot, for any reason, be carried out as prescribed by the conceptual model. These operational failures shall serve as the basis to discard the unit.

3.10.1 Experimental unit declaration

An experimental unit will be declared when clouds in the target area pair satisfy the following qualification criterion:

> Multiple convective clouds with at least 1 kilometer, but no more than 3 kilometers, in depth are present in *both* target areas. The presence of one or two isolated convective clouds at least 1 kilometer in depth in each area does not satisfy this criterion, but a line of clouds in each area with only a few towers 1 to 3 kilometers in depth does satisfy this criterion.

3.10.2 Flight procedures

The flight and seeding procedures to be implemented in the warm cloud seeding demonstration project are described in "Volume 3 -Demonstration Project Operations Plan" of this PASA Final Report. Two CASA aircraft carry out seeding in the target area randomly selected for treatment. The two CASA aircraft fly together during seeding operations, simultaneously seeding at two prescribed altitudes. Thus, the seeded clouds will receive a double dose of $CaCl_2$ particles.

The AeroCommander aircraft will be used to confirm whether clouds in the two target areas meet the warm cloud seeding qualification criteria, and to make preseeding and postseeding measurements.

3.11 Projected Duration of the Demonstration Project

Sample size estimates for the warm cloud demonstration project are discussed in detail in appendix E and summarized here. Assuming, for example, that seeding increases rainfall by 10 percent [SMF (seeding multiplicative factor) = 1.10], table 3.1 gives the sample sizes required to achieve probabilities of detection of 0.80 and 0.90 at a significance level of 0.05.

Table 3.1. - Estimation of the number of samples that will be required in the warm cloud seeding demonstration project to reach a statistical significance level of 0.05 for a power of 0.80 and 0.90, assuming an increase in rainfall caused by seeding of 10 percent.

		Sample Size for Seeding Model	
Target Pair	Power	Multiplicative	Mult + Add
West	0.80	93	75
	0.90	144	102
East	0.80	99	64
	0.90	195	104

These results indicate that obtaining the required number of samples would take from 2 to 3 years, assuming that 60 seeding opportunities occur per year and that all are successfully implemented. Obtaining the required number of samples will likely take 4 to 5 years (a conservative estimate) because the number of opportunities is likely to vary and some seeding opportunities will be missed because of errors in execution or equipment failures. *It is emphasized that the number of samples will determine the duration of the experiment.*

3.12 Statistical Evaluation

3.12.1 Primary response variables

All the primary response variables will be based on radar-rain gauge adjusted rainfall data in each target area in each experimental unit and the corresponding downwind area, and will include the following parameters:

1. Rainfall volume.
2. Rainfall area.
3. Spatial distribution of rainfall amount.
4. Time after seeding that rain first appears.

3.12.2 Data Stratifications

To confirm or better understand the conceptual model of warm cloud hygroscopic seeding, the data for each target area pair will be stratified as follows:

1. By cloud depth at the time of seeding.
2. By the presence or absence of radar echoes in either target of the target pair at the time of seeding.
3. By whether the eventual cloud top temperature is warmer or colder than -5 °C.
4. By the time elapsed after the experimental unit is qualified until the seeding operation is actually carried out.

The best results are expected for the stratification combination of moderately deep (about 2 kilometers) clouds with no radar echo at the time of seeding. In view of the results of the numerical modeling experiments given in appendix D, it remains to be seen whether seeding will have a greater effect on the cold clouds or warm clouds. This aspect is, perhaps, the most interesting of the warm cloud seeding demonstration project from both the scientific and user viewpoints.

3.12.3 Statistical procedures

The analysis procedure used in the sample size simulations (see appendix E) is readily applicable to the evaluation of the demonstration project. Therefore, upon collection, quality checking, and archival of the field data, these procedures can be applied as follows:

1. Computation of the specified primary response variables for each experimental unit.
2. Estimation of the treatment effect on rainfall for the experiment as a whole and each stratification subset. The root double ratio will be used to estimate the sign and magnitude of the seeding effect to account for possible biases in rainfall between the targets in a target pair.

3. Sorting of the data by preselected stratification as well as pooled, and preprocessed in preparation for application of the statistical test. When the north target is seeded, the data set will consist of the difference between the actual seeded rainfall and the predicted rainfall that would have occurred in the absence of seeding. The predicted non-seeded rainfall will be estimated from the regression equation of north rain on south rain forced through the origin. When the south target is seeded, the data set will consist of the difference between the predicted rainfall that would have occurred in the absence of seeding and the actual seeded rainfall. The predicted non-seeded rainfall will be estimated from the regression equation of south rain on north rain forced through the origin.

4. Development of *P*-values by application of the MRPP (Multi-Response Permutation Procedure).

5. Interpretation of *P*-values in terms of the conceptual model.

6. Acceptance or rejection of the null hypotheses.

3.13 Physical Evaluation

These analyses will focus on examining seeding effects in the treatment units and main target clouds. The seeding effect is expected to be greatest in the main target cloud which receives the greatest treatment, and will get increasingly weaker as the ratio of the number of clouds seeded to the total number in the area being examined decreases, but this expectation remains to be confirmed. The purpose of the physical evaluation is to better understand the chain of physical events following hygroscopic particle seeding of both warm and cold clouds, and to obtain physical evidence of these effects.

3.13.1 Evaluation of the cloud physics data base

The only measurements taken by the cloud physics aircraft (AeroCommander) that will be used in the evaluation will be measurements of aircraft position, the existence or non-existence of clouds, and cloud base and top heights in the experimental units. Failure of the aircraft DAS (data acquisition system) is not a viable reason for "standing down" or abandoning an experimental unit because all of these measurements can be obtained by observation and hand recording of the standard aircraft instruments.

3.13.2 Processing the radar data

3.13.2.1 Creation of the volume-scan data base

The radar at Omkoi will monitor and record the three-dimensional structure of the convective rain cells during its scan of the whole troposphere in the study every 5 minutes. These data will be the primary source of information for the scientific evaluation of the effect of seeding on warm clouds. In creating this data base, the calibration curve will be used to obtain reflectivity values after accounting for noise and any attenuation. Reflectivity (Z) will be converted to rainfall rate (R) by using the Z-R relationship that is appropriate for Thailand.

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The demonstration project has the benefit of 45 to 48 recording rain gauges within the study area. Comparisons between rain gauge and radar rainfall estimates should be carried out, and these studies are expected to result in improved methods of radar estimation of rainfall.

3.13.2.2 Tracking the cells

As in earlier work in Florida (Gagin et al., 1985) and in Texas (Rosenfeld and Woodley, 1989), convective cells in the treated and nontreated target areas will be defined as entities with at least three closed radar reflectivity isolines spaced at 1-dBZ intervals at the cloud-base level. All radar echoes greater than the noise level will be partitioned between these entities; the division lines will coincide with the trough lines on the reflectivity map.

Once these entities have been identified, the method of Rosenfeld (1987) will be used to track the cells in three dimensions. Two tracking approaches will be used: the "short track" and the "long track." The "short track" approach tracks cells until they dissipate. This approach works best for cells that never merge with their neighbors. For merging cells, however, the "long track" approach will be used. The "long track" approach allows for the tracking of a subject cell, even if it merges with a neighbor, until it satisfies certain truncation criteria (see Rosenfeld and Woodley, 1989). The "long track" approach allows for longer tracking (hence the name), but results in some cell duplication. Each approach has advantages and disadvantages. For each cell tracked, the following parameters will be calculated:

1. DUR = The time (in minutes) after the first scan until the cell identity is lost.

2. H_{max} = The maximum echo height (in kilometers mean sea level) of the cell.

3. Z_{max} = The maximum reflectivity (in dBZ) at cloud base level.

4. A_{max} = The maximum area (in square kilometers) at cloud base level.

5. RVR_{max} = Maximum rain volume rate (in 10^3 cubic meters per hour) through cloud base level.

6. R_{vol} = Total rain volume yield in units of 10^3 cubic meters.

The mean time-dependent translation vector of all tracked cells in the radar field will be used to advect the experimental units and the treatment coordinates.

The relationships between the maximum vertical dimensions of the cells and their other lifetime properties for treated cells (target area randomly selected for treatment) and non-treated target cells will be calculated. This calculation will be done to determine whether a relationship exists between cell height and the other cell properties, and whether the relationships are different for the seeded clouds.

3.13.3 Search for seeding effects

3.13.3.1 Accounting for natural biases

At least some of the natural variability must be taken into account in any analysis of seeding effect. The approach will be that pioneered by Gagin et al. (1986). If the properties of control cells were perfectly correlated with the cells within a NS experimental unit, then the seeding effect could be determined by the *DR* (double ratio):

$$DR = SR/CR$$

where *SR* (single ratio) is the simple apparent seeding effect, given by:

$$SR = (\ )T_{hyg}/(\ )T_{sim}$$

and *CR* (control ratio) is the bias caused by the natural variability, given by:

$$CR = (\ )C_{hyg}/(\ )C_{sim}$$

where the values in parentheses can be the mean of any of the lifetime properties of the cells; *T* stands for treated cells, *C* for control cells; "*hyg*" denotes the cells in which hygroscopic chemical seeding took place, and "*sim*" denotes the cells in which seeding was simulated.

3.13.3.2 Statistical significance tests

Estimation of the treatment effect for each randomization and stratification will be accomplished by computation of the ratio of the mean response variable value for the seeded sample to the comparable mean value for the nonseeded sample using a nonparametric test procedure such as the Wilcoxon Test, the Mann-Whitney Test, or the MRPP.

3.13.3.3 Seed versus no-seed comparisons

Several analyses will be pursued in the S versus NS comparisons. The first will be comparison of means, SR, and DR for the various response variables as a function of treatment decision for each data stratification. In addition, plots of mean cell properties versus time for the S and NS samples will be constructed. Finally, time-height reflectivity plots will be composited for the S and NS cases. The time that treatment begins will be used as the "0" time reference in all time plots.

Analyses for seeding effects in pooled samples will be made once the comparisons for each data stratification have been made. Pooling of samples will be done wherever it is physically and statistically prudent to do so. This pooling will permit the analysis of larger samples and thereby improve the chance of obtaining statistically significant results, although this statistical significance is unlikely to occur in only one field season.

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4. DATA COLLECTION, MANAGEMENT AND REPORTING

Data are the lifeblood of any experiment, yet some projects suffer in this area. Considerable effort will be put into this area as detailed in volume 3 to ensure good data collection and quality control. Most importantly, a data manager at the home office of RRRDI, along with an assistant at the field project headquarters, should be identified to protect this important project resource.

All project activities must be reported in documents that are readily available to people who have an interest in the program. Preparation and distribution of such documents prior to, during, and after experimentation make the overall program more credible. Such openness is simply good policy, both from a public relations and from a scientific standpoint. This combined Design Document and Operations Plan should be only the first in a series of reports about the Phase 2 cloud seeding experiments.

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APPENDIX A

Precipitation Enhancement: A Scientific Challenge

/ / /

A.1 Introduction

Water is the lifeblood of a nation that determines the quality of life of its people. The uses of water and its cost and price are seen throughout the general economy. Thus, it is a matter of great concern that the fresh water supplies of the world are rapidly becoming inadequate to serve a growing population and its attendant needs for food, fiber, and energy production. The growing population is pushing the environment to the limits of its carrying capacity. Some economists are predicting that fresh water will supplant oil as the world's problem commodity by the end of the twentieth century. In the arid and semiarid regions of the world, water has been a problem commodity for some time. One only has to look at the situation in Ethiopia to see the enormous impacts that the lack of water can have on a nation and its people.

No "normal" amount of precipitation really exists. Most years have much less or much more precipitation than the historical average. Half the average or twice the average precipitation is not uncommon, and year-to-year variations can fluctuate as much as 240 percent in the extreme. Many regions, especially those that are semiarid, usually experience more years with below-average precipitation than above-average precipitation. Periodically, droughts occur where the prolonged periods of below-average precipitation cause a serious hydrologic imbalance, and the resulting water supply shortage has a dramatic impact on the economy of the affected area. As the gap between water supply and demand narrows, periods of below-average precipitation that are less extensive in duration, space, and magnitude than those of droughts are having increasingly greater socioeconomic impacts. In view of the general moratorium on the construction of new water storage dams, which help cushion the impacts caused during episodes of below-average precipitation, the vulnerability of the economy to these episodes will almost certainly increase.

The task of overcoming natural deficits in precipitation and the unpredictable variability in precipitation from year-to-year is formidable. No one best solution can solve the resulting water problems. A combination of conservation and augmentation measures in an integrated water management strategy will likely be necessary. Modern agricultural and engineering practices will have to be used to stretch available water supplies, and new conservation and augmentation technologies will have to be developed.

Water augmentation through precipitation enhancement, either as additional rain or additional snowpack, may be the most promising source of new water for some regions of the world.

The science of precipitation enhancement and its application as a water augmentation tool are discussed in this paper. The primary purpose of the discussion, which will focus on concepts only, is to stimulate research and experiments that will improve the scientific foundation of precipitation enhancement and to foster user-oriented applications that are consistent with the state of the science. In the opinion of this writer, realization of the full range of applications of precipitation enhancement and its benefits to the world community that it is meant to serve will only result from steady improvement in the scientific foundation of precipitation enhancement.

The issues to be discussed are mainly concerned with the scientific and technical aspects of precipitation enhancement and relate primarily to the question—can we do it? Because precipitation enhancement is not an end in itself, but rather a means of satisfying human

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needs, it is also relevant to ask—should we do it? The answer to this question involves consideration of issues that go beyond those of a scientific and technical nature. Precipitation enhancement must be perceived as satisfying a range of social, economic, environmental, legal, and political concerns if it is to successfully compete among alternatives for scarce funds and be implemented as part of public policy. The lack of elaboration on the societal issues should not be misconstrued as an indication that they are relatively less important.

A.2 Water Management Role

Precipitation is a renewable atmospheric resource that is a fundamental part of the hydrological cycle. It is a significant component of the water resources on which people have come to rely and could be managed, like stored water supplies, to better serve the needs of society. Although efforts to enhance precipitation through cloud seeding are not of recent origin, the concept that the atmosphere contains a water resource that can be managed in the same way as other natural resources is a comparatively recent idea.

Precipitation enhancement through cloud seeding is an attractive water management option. It is a cost effective means of augmenting the quantity of water while improving its quality. It does not require major permanent construction and large fixed operation and maintenance costs. Rather, it serves to improve the efficiency of existing capital structures, such as water storage dams, hydroelectric power generation plants, and irrigation systems. Moreover, a decision to employ cloud seeding is reversible on a year-to-year or even storm-to-storm basis within a season, should basin hydrology, weather patterns, or public interests so dictate.

Precipitation enhancement could help even out variations and ease shortages by adding to water supplies in two ways. It could be used to recharge and augment the amount of water stored in reservoirs and aquifers whenever seeding opportunities arise and the hydrologic situation warrants. The added water would then be available to draw on when and where needed, and could also be used to generate low cost, environmentally clean electricity. Cloud seeding could also be used for direct application of water on croplands and rangelands whenever seeding opportunities occur in the right place and time to be of benefit. This technique would reduce the depletion of stored water supplies and the costs associated with pumping it to its desired location. In short, precipitation enhancement is appropriate for use on a year-round basis as an integral part of a long-term, comprehensive water management protocol.

Unfortunately, precipitation enhancement is viewed by many potential users only as a drought relief measure. Operational programs increase during drought episodes, apparently with the expectation that water deficits that took years to develop will be quickly replenished. Precipitation enhancement is often invoked as a desperation measure during drought in an attempt to alleviate the severe impacts already being experienced. This practice is encouraged, in part, by the relatively quick start-up time and low cost of emergency cloud seeding operations in comparison to other potential drought relief measures. However, reaction to crisis must be replaced by proactive planning and preparation for drought to lessen its impact. The timely and prudent application of well thought out plans for scientifically-sound precipitation enhancement is technically superior and more cost effective than a hastily mobilized, unevaluated response to crisis.

Although cloud conditions during drought and below-average precipitation years are generally atypical, seeding opportunities do occur, but usually with less frequency than they occur during average precipitation and wet years. Drought and below-average precipitation years are characterized mainly by a reduction in the frequency of occurrence of the relatively few cloud systems which produce large precipitation events that contribute most to the seasonal precipitation of an area, cloud systems which are usually considered not suitable for cloud seeding. Percentage increases in precipitation through cloud seeding might even be greater in dry years, but the incremental amounts tend to be smaller. The moderate amount of additional precipitation from cloud seeding will not provide quick and total relief from drought, but it will help, especially if it occurs at crucial stages in crop growth and in crucial locales for reservoir storage. A program of precipitation enhancement is more effective in cushioning the impact of drought if it is also used during average precipitation years, and even wet years, to build soil moisture, to improve cropland, and to increase water in storage.

A.3 Science of Precipitation Enhancement

Prudent application of cloud seeding requires baseline knowledge of the dynamic structure of the environment and the microphysical characteristics of the resulting clouds. Thermal and dynamic instabilities in the atmosphere give rise to the vertical air motions that determine the number and size of clouds that will develop in an area. Microphysical processes operate within this governing dynamic framework to convert into precipitation the water vapor that is made available by the vertical motions. Precipitation initiation and development involves complex physical mechanisms, some of which often proceed simultaneously in a cloud but at different rates. Precipitation can result from either all liquid microphysical processes, mixed water-ice phase microphysical processes, or all ice phase microphysical processes. The feasibility of cloud seeding and the choice of an appropriate seeding strategy depend on knowledge of the dynamic and microphysical processes that are dominant in the cloud systems to be seeded. Understanding of the dynamic-microphysical interactions is particularly important because cloud seeding will be most effective if the relatively small direct effects of seeding can stimulate the natural physical processes to produce enhanced precipitation.

The science of precipitation enhancement requires consideration of four (4) major technical issues:

1. The physical hypothesis,
2. The recognition of seeding opportunities,
3. The implementation of a seeding strategy, and
4. The evaluation of the effects of seeding.

The main tools of the science of precipitation enhancement are numerical cloud modeling and field experimentation, preferably used in concert.

A.3.1 Physical hypothesis

The scientific basis for enhancing precipitation by cloud seeding rests on two different physical hypotheses, generally called the static seeding concept and the dynamic seeding concept. The static seeding concept has been applied to cold orographic clouds for the purpose of snowpack enhancement and both warm and cold convective clouds for the purpose of rain enhancement. The dynamic seeding concept has been applied only to cold convective clouds for the purpose of rain enhancement.

The static seeding concept, also known as seeding for microphysical effects, is based on *observations* that precipitation development in some clouds is frequently inefficient and on the *expectation* that the natural precipitation process can be made more efficient by the introduction of additional precipitation embryos through seeding. The presence of water in a cloud that is or is expected to be underused by the cloud's natural precipitation process is generally taken as evidence of the cloud's precipitation inefficiency. For example, the precipitation from convective clouds is frequently only 10 to 40 percent of the total cloud water condensed. The static seeding strategy is to create an optimum number of precipitation embryos for the available liquid water and to initiate the precipitation process earlier and, in some cases, lower in altitude in the developing cloud than would occur naturally. If too many potential precipitation embryos for the available liquid water are produced, then none may grow large enough to fall out, and the cloud is said to be overseeded.

For cold clouds, glaciogenic seeding agents, such as AgI and dry ice, are used to stimulate precipitation development. The goal of the seeding is to produce about 10 to 20 ice crystals per liter. The ice crystals grow to precipitation embryo size by vapor deposition at the expense of the supercooled water droplets because the saturated vapor pressure over ice is less than that over supercooled liquid at the same temperature. For warm clouds, precipitation development is stimulated by the introduction of hygroscopic chemical particles, which are either precipitation embryo size already or can rapidly grow to precipitation embryo size by condensation. The usual dosage of hygroscopic particles is 100 to 1000 kilograms per cloud.

The dynamic seeding concept, also known as seeding for dynamic effects, is based on *observations* that precipitation from large clouds is significantly greater than that from smaller clouds, and the *expectation* that larger clouds can be produced by invigorating the updraft through seeding. A twofold increase in convective rain cell height corresponds to a factor of ten increase in total rain volume, and the taller convective rain cells produce the larger total rainfall volumes by virtue of larger precipitating areas, rain rates, and rain durations. The dynamic seeding strategy is to glaciate the cloud updrafts earlier in time, lower in the cloud, and more rapidly than would occur naturally and, thereby, release large amounts of heat in the updraft that would cause enhanced growth of the cloud in both depth and breadth. The rapid glaciation of the cloud updraft is triggered by seeding with a massive amount of glaciogenic agent, with the aim of producing about 100 ice crystals per liter.

The intended effect of the static and dynamic seeding concepts and the difference between them can be summarized by examining the basic expression for the precipitation efficiency of a cloud:

$$P = E \times C$$

where P is the total precipitation from a cloud, E is the precipitation efficiency of the cloud, and C is the total amount of water condensed in the cloud. Static seeding is intended to enhance precipitation, P, by improving the cloud's precipitation efficiency, E, through a seeding-induced alteration of the cloud's microphysical properties only. Changes in the dynamic properties of the cloud that may occur as a result of the seeding are expected to be of little consequence and are not part of the cause-and-effect relationship in the static seeding hypothesis. Dynamic seeding, on the other hand, is intended to enhance precipitation, P, by increasing the total amount of condensed water in the cloud, C, through a seeding-induced increase in the dimensions of the cloud. In dynamic seeding, the microphysical effects of seeding are intended to produce large, concomitant dynamic effects that are central to the cause-and-effect relationship in the dynamic seeding hypothesis. The effect of dynamic seeding on the cloud's precipitation efficiency, E, is not clear; however, it is likely that it is initially inhibited and, subsequently, becomes either the same or greater than it would have been in the absence of seeding.

A.3.2 Seedability

Seedability criteria are a practical expression of the physical hypothesis. They are used in an attempt to distinguish and select among those clouds that result in increases, no effect, and decreases in precipitation when seeded. In addition, they are used to help control variability in the evaluation of a seeding experiment.

According to the static seeding hypothesis, a cloud is postulated to be seedable if the coalescence process in the cloud is inefficient, and if it contains or will contain cloud water that exceeds that required by the cloud's natural precipitation process, that will not be eroded by competitive depletion processes, and that will last long enough in sufficient quantities to permit the growth of additional precipitation particles to sizes that can reach the ground. No generally accepted postulate exists that sets forth the physical criteria for seedability according to the dynamic seeding hypothesis. However, the dynamic seeding hypothesis implies that the static seedability criteria should apply as dynamic seedability criteria as well, with one important difference and one important addition. The important difference is that the coalescence process in a dynamically seedable cloud should be efficient. The important addition is that the atmospheric structure should be such that it can support the seeding-induced growth of larger clouds.

It can be seen that a condition of seedability is the net result of interacting, rate-dependent, microphysical and dynamic processes in clouds. Seedable conditions will exist for only a relatively short period of time, usually referred to as a "seeding time window." The "seeding time window" occurs primarily during the early stages of cloud growth when the initiation of precipitation development can still be influenced. The fundamental requirement of seedability criteria is to recognize a seeding opportunity early enough to permit the execution of the seeding within the "seeding time window."

Recognizing or forecasting seedable conditions has proven to be extremely difficult. The approach has been to identify an initial set of environmental and cloud conditions which are believed, from analytical and/or numerical cloud model studies, to represent a weather situation in which some of the clouds will respond positively to seeding in accordance with one of the physical hypotheses. Thus, a day is considered to have seeding potential if it is characterized by the requisite environmental conditions, and a specific cloud occurring on such a day is considered seedable if it contains the requisite microphysical/dynamic properties at the time of selection. Both sets of criteria are necessary because cloud studies have shown that only a fraction of otherwise promising clouds last long enough to be seedable, some of which do, and some of which do not, develop precipitation naturally.

The criteria for determining whether a day has seeding potential, also known as experimental day declaration criteria, are generally based on thermodynamic and synoptic parameters such as precipitable water, stability, and wind conditions. The threshold value of these parameters is generally determined by linear or multiple regression analysis, with the occurrence of rain as the discriminant parameter. Precipitation enhancement programs based on the dynamic seeding concept use a steady-state numerical cloud model to predict dynamic seedability. Experimental day declaration criteria are usually the only basis for deciding whether or not to seed in most area-wide seeding experiments and operational seeding programs.

Early approaches to determine cloud seedability were based on real-time observations and the experimenter's judgment as to the future development of the cloud. Experimenters applied such criteria as the cloud's visual appearance and top temperature, and indications that the cloud was growing, that it would last at least 30 minutes, that it would not be affected by surrounding clouds, and that it did not rain prior to selection. With the advent of cloud physics aircraft, in situ microphysical data collected during a pretreatment aircraft pass have been incorporated into the cloud selection criteria. Final selection of a cloud for treatment is made if such characteristics as liquid water content, ice crystal concentration, vertical velocity, and cloud depth are within predetermined bounds.

The prospect of potentially more effective indices of seedability have emerged from cloud physics research and analyses of precipitation enhancement experiments. Consider first the findings related to cold cloud seeding. Cloud-base temperature has been shown to be a good indicator of whether the dominant precipitation embryos will likely be ice crystals or large drops; the transition from one to the other occurs at a cloud-base temperature of about 10 °C. As such, the temperature indicates whether coalescence in the cloud will be inactive or active and, thereby, whether the static seeding concept or dynamic seeding concept, respectively, is most applicable to the cloud. A warm-side and cold-side cloud-top temperature limit to seedability has also been found in cold convective clouds. On the warm side, static seeding has been shown to be the most effective at a temperature level of -12 to -15 °C. For dynamic seeding, the warm-side temperature limit is that at which glaciogenic seeding agents become effective. On the cold side, the cloud-top temperature limit to static seedability has been found to be about -25 °C, and precipitation decreases are associated with seeded clouds having cloud-top temperatures colder than -40 °C.

As with cold clouds, cloud-base temperature for warm clouds is a good indicator of the cloud's coalescence efficiency. A cloud depth of at least 1.7 kilometers is required for hygroscopic particle seeding to result in meaningful rain showers on the ground. On the other hand, the coalescence process will be well developed naturally if the cloud depth exceeds about 3 kilometers.

The above findings suggest that in addition to a "seeding time window," a "cloud temperature window" or, perhaps, a "cloud depth window" exists that is conducive to seeding. Because the size of a cloud is, to a large extent, determined by the thermodynamic structure of the environment in which the cloud evolves, rawinsonde data are used as the basis for estimating natural cloud-base and cloud-top temperatures, and the height to which a cloud will grow when dynamically seeded. Numerical cloud models are a principal tool in making these estimates. However, this approach has not yet proven to be reliable in a predictive sense because of the difficulty in obtaining representative rawinsonde soundings and because of the shortcomings of the cloud models that can be used in real time.

A.3.3 Seeding execution

Once a cloud is deemed seedable according to some predetermined seedability criteria, the seeding operation must be executed in accordance with the appropriate precipitation enhancement seeding hypothesis. Proper implementation of each of the seeding concepts depends on introducing the proper size and concentration of seeding material in the proper place and time in the developing cloud. Attempts to achieve the seeding objective have involved the use of dry ice and a variety of AgI agents for cold clouds, and a variety of hygroscopic chemicals for warm clouds. The implementation has involved a wide range of seeding rates and seeding modes, including areal broadcast and cloud-by-cloud seeding with on-top, in-cloud, cloud base, subcloud layer, and ground-based delivery systems. The implementation has proven to be an extremely difficult objective to achieve, involving the joint solution of such complex processes as seeding agent effectiveness and the transport and dispersion of seeding particles and/or ice crystals. Proper execution of the seeding objective continues to be a key problem in the science of precipitation enhancement. In this writer's opinion, the diverse results of past research and seeding tests are caused in large part by the inability to execute the seeding operation as intended and are not necessarily a reflection of the validity of the seeding hypotheses.

A.3.3.1 Seeding materials

A.3.3.1.1 Glaciogenic agents

The seeding hypothesis for cold cloud seeding is initiated by producing a specific concentration of ice crystals at a specific temperature in the growing cloud. Dry ice and AgI are the usual seeding agents that are used to produce the ice crystals.

The effectiveness of dry ice in producing ice crystals is fairly well known. Dry ice is an attractive seeding agent because it produces ice crystals virtually instantaneously, and the concentration it produces is only mildly temperature-dependent. As such, dry ice seeding introduces a measure of certainty in properly initiating the cold cloud seeding hypothesis. Dry ice has the further advantage of being effective at temperatures as warm as -2 °C. The disadvantages of dry ice as a seeding agent are its relatively high payload requirement, its short "shelf life," and the limitation in seeding mode to cloud-by-cloud, on-top, or in-cloud seeding.

The advantages and disadvantages of AgI as a seeding agent are essentially opposite to that of dry ice. AgI has the following advantages: a long "shelf life," a relatively low payload requirement, and the ability to be readily dispersed by any of the seeding modes. However, it has the disadvantage that its effectiveness varies with AgI chemical composition, dispensing mode, temperature and residence time in the cloud, and cloud characteristics, which makes it difficult to control or even precisely know the concentration and location of the ice crystals that are produced. The effective threshold of activity for most AgI seeding agents is about -9 to -10 °C.

A.3.3.1.2 Hygroscopic agents

Hygroscopic particles, either as a dry powder or solution droplets, are used to initiate the warm cloud seeding hypothesis. The effectiveness of hygroscopic chemicals depends primarily on the size, uniformity, and concentration of the particles, and secondarily on its affinity for water vapor. However, the fact that the particles are hygroscopic makes it very difficult to obtain and maintain the size, uniformity, and concentration required for maximum effectiveness.

The hygroscopic particle seeding technique has two additional inherent problems. The first problem relates to the logistics involved in carrying out the seeding operation. Even if the particles are optimally sized, the amount of seeding material required to affect a significant cloud volume requires the use of large aircraft to carry the required payloads. The use of dry powders rather than hygroscopic solutions is more advantageous in this regard because a greater amount of hygroscopic agent can be carried in a fixed payload. In an attempt to improve the payload effectiveness of dry powders, some experimenters have seeded with smaller particles at cloud base with the expectation that they will grow rapidly by condensation to precipitation embryo size. However, obtaining and maintaining the size and uniformity of the dry powders is more difficult, and failure to do so rapidly diminishes the effectiveness of the payload. The second problem arises from the fact that many of the hygroscopic chemicals used in warm cloud seeding are either caustic, corrosive, or both. The hydroxides and chlorides have the most undesirable side effects; organic chemicals have fewer side effects.

Recently, South African scientists (Mather and Terblanche, 1992) have experimented with the seeding of cumulus clouds using hygroscopic flares. The flares are burned in the subcloud layer prior to cloud development to make the nuclei spectrum on which the cloud droplets will eventually form more maritime in character and, thereby, improve the precipitation efficiency of the clouds. These flares, if they prove successful, solve many of the problems associated with the use of hygroscopic chemicals. However, their effectiveness is highly dependent on the existing natural nuclei spectrum.

A.3.3.2 Transport and dispersion

All seeding materials are initially dispensed in highly concentrated dosages; vertical columns are produced by airborne drops of dry ice pellets or AgI pyrotechnics. Horizontal lines are produced by airborne AgI-acetone generators. End-burning AgI flares and hygroscopic particle dispensers, and ground-based AgI-acetone burners and hygroscopic particle blowers act as point sources. Transport and dispersion of the seeding material and/or the ice crystals they produce are then relied on to achieve the proper concentration in the targeted cloud volume at the appropriate time in the evolving cloud as required by the appropriate physical hypothesis. Although the implicit assumption is that no penalty results from the transient high concentrations of seeding material/ice crystals that are produced by the seeding process, in some cases of static seeding, the local "overseeding" results in unpostulated effects.

Cloud-top or in-cloud seeding provides the greatest assurance that the seeding material/ice crystals will be introduced at the appropriate place and time in the cloud, but the time and vertical distance available for dispersion throughout the volume to be affected are quite limited. In the case of AgI and hygroscopic particle seeding, the seeding material can be dispensed farther from the intended target, either upwind, at cloud base, or from the ground, to increase the time available for volume dispersion and dilution. However, targeting and timing of the seeding effect become more difficult and uncertain. These problems are particularly acute in the case of ground-based seeding, which also suffers from an inability to control seeding coverage and seeding concentrations.

A.3.4 Evaluation

For many years, "black-box" experiments were used to test precipitation enhancement concepts; that is, a particular seeding technique was applied and only one output, namely precipitation on the ground, was measured and analyzed. It is now clear that a "black-box" experiment does not provide a scientifically acceptable test of a seeding concept, regardless of the outcome, because it does not provide scientific evidence which physically relates the seeding to the measured effect. If the experiment results in no detected change in precipitation, no scientific basis exists for concluding that the underlying physical hypothesis is not valid. If the experimental results are inconclusive, as has been the case in most experiments, no basis exists for determining why the experiment turned out as it did and what changes in the seeding strategy, if any, can be made to improve the results. And if the experiment results in a statistically significant change in precipitation, no scientific basis exists for transferring the seeding strategy to other places and times.

In all applications, provision should be made for a physical-statistical evaluation of the results of the cloud seeding. The physical processes within the cloud should be monitored to the extent possible in order to improve the understanding of natural and modified precipitation processes, with the aims of establishing whether cloud seeding in accordance with a prescribed physical hypothesis can reliably and repeatedly produce a change in rainfall and identifying the specific cloud conditions to which it applies. The statistical component is essential in this regard to avoid bias in the conduct and evaluation of the cloud seeding, and to cope with the large variability in the physical data. Statistics is the tool which allows detection with confidence and in a reasonable period of time the physically postulated changes, if any, that seeding may cause, changes which are small compared to the natural variability. Random allocation of the seeding events is the most efficient way to achieve this goal.

A.4 Some Decisionmaking Considerations

A properly conducted physical-statistical evaluation of a precipitation enhancement campaign also contributes to the information base needed to assess the risk in applying that cloud seeding concept. The probability of occurrence of a future state of nature which defines a risk decision situation is well represented by the statistical parameters used in the evaluation of scientifically well-designed precipitation enhancement campaigns. According to hypothesis testing principles, the information about the effectiveness of a cloud seeding intervention is given by three key parameters:

α = the level of significance of the test, defined as the probability of rejecting the null hypothesis when in fact it is true. α is also known as the Type I error, or producer's (scientist's) risk.

π = the power of the test defined as the probability of correctly rejecting the null hypothesis. It is equal to $1-\beta$, where β is the probability of accepting the null hypothesis when in fact it is false. β is also known as the Type II error, or consumer's (user's) risk.

δ = the estimated value of a multiplicative increase in precipitation.

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Using these values, an expression for a "risk-weighted" benefit-cost ratio can be derived. The benefit-cost analysis approach is used because water resource projects have been evaluated by this method for over 50 years. In particular, benefit-cost ratios have been used to show that water projects are justified and to aid in the selection of projects among competing alternatives.

First, an expression for the mathematical expectation of profit, P, from engaging in a precipitation enhancement project is formed.

$$P = \pi(\alpha,\delta)\,(B - C) - \alpha\, C \qquad (1)$$

where B is the project benefits and C is project costs.

A form involving the benefit-cost ratio is obtained by dividing both sides of (1) by C.

$$P^{\circ} = \pi(\alpha,\delta)\,(V - 1) - \alpha \qquad (2)$$

where $P^{\circ}=P/C$, the profit-cost ratio, and $V=B/C$, the benefit-cost ratio.

The expression for the "risk-weighted" benefit-cost ratio, V°, is obtained by substituting in (2) the fundamental relationship:

$$V^{\circ} = P^{\circ} + 1$$

$$V^{\circ} = \pi(\alpha,\delta)\,(V - 1) - \alpha + 1 \qquad (3)$$

It can be seen from (3) that the "risk-weighted" benefit-cost ratio, V°, will always be less than the computed benefit-cost ratio, V, as long as uncertainty exists in the outcome of cloud seeding for precipitation enhancement. If and when knowledge about precipitation enhancement reaches a decision situation of certainty, that is, the outcome of cloud seeding will be known exactly, then $\pi(\alpha,\delta) = 1$ and $\alpha = 0$. In this circumstance, no scientific risk will exist in applying precipitation enhancement, and $V^{\circ} = V$.

The evaluation of most precipitation enhancement projects has focused primarily on α and δ, and to a much lesser extent on π (or β). The scientists who have conducted these projects have tried to maximize their level of confidence in the physical effectiveness of the intervention. However, it can be seen from (3) that π (or β) is more important than α in minimizing the user's risk in applying the intervention. Therefore, more attention must be focused on these parameters in future precipitation enhancement projects. In particular, precipitation enhancement projects designed to minimize the user's risk in applying the intervention while maximizing the scientist's level of confidence in the physical effectiveness of the intervention will have to be longer in duration than those projects conducted heretofore.

Finally, it is interesting to note that for typical values of benefit-cost ratios for precipitation enhancement projects ($V = 3$ to 30) and typical values of π and α for such projects ($\pi = 0.5$ and $\alpha = 0.05$), the "risk-weighted" benefit-cost ratios are still relatively large, especially when compared to the benefit-cost ratio of most U.S. capital construction water resources development projects ($V = 1$ to 2).

A.5 Conclusions

From a rigorous scientific standpoint, cloud seeding to increase precipitation must be regarded as an emerging technology. The accumulating evidence that certain weather conditions can, under the proper circumstances, be significantly altered by carefully controlled seeding is based primarily on statistical indications which do not yet have the necessary physical support to explain and verify the cause-and-effect relationship responsible for the statistically-detected change. Where indications of precipitation enhancement have been suggested, replication of the results are required before any of the seeding technologies can be considered scientifically proven. However, despite residual uncertainties in the evidence for precipitation enhancement, the conclusions reached over 2 decades ago that certain kinds of precipitation can be increased on the order of 10 percent have been generally supported.

While the research community labors to place precipitation enhancement on a secure scientific foundation, people with major water interests at stake are investing in operational cloud seeding based on current knowledge. The need for more precipitation has created a demand for cloud seeding even in the face of sometimes outspoken scientific skepticism. An analysis of the World Meteorological Organization's Registers of National Weather Modification Projects reveals the increasing worldwide activity in precipitation enhancement in response to the increasing need for additional water resources. The upward trend is punctuated by spurts of additional activity associated with the occurrence of droughts. The sponsors of precipitation enhancement projects include National Governments, local governments, and user groups such as agricultural cooperatives, water conservancy districts, irrigation authorities, and utilities. These users are attempting to reap the benefits of the emerging technology, believing that the scientific risks and costs are small compared to the benefits that might be gained. They are applying decision standards involving risk levels that are common to their activities, and not those commonly used by scientists. The risk levels of the users tend to be higher than those of scientists, and the user's risk level varies according to the externalities that affect their activities. Scientist's risk levels are constant and always very conservative.

The fact of the matter is that the current state of the science does not permit an accurate prediction of the exact state of nature that will result following a given cloud seeding operation, a situation that is likely to improve only slowly with time. However, the residual uncertainties need not be a deterrent to application of the technology in those cases where the information is sufficient to assess the probability of occurrence (risk level) for each of the likely future outcomes. Thus, the best we can do is to find situations where cloud seeding can be done within risk levels acceptable to the user to achieve the desired outcome. Some techniques that satisfy this criteria are now available for use, and more can be expected in the future as the science of precipitation enhancement progresses.

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APPENDIX B

Testing of Dynamic Cold Cloud Seeding Concepts in Thailand

Part I: Experimental Design and its Implementation
Part II: Results of Cloud-Microphysical and Radar Analyses

(Abbreviated versions of the two papers in this appendix have been accepted for publication in the *Journal of Weather Modification, 1994*)

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PART I: EXPERIMENTAL DESIGN AND ITS IMPLEMENTATION

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ABSTRACT

Dynamic, cold cloud seeding concepts are being tested in Thailand in the context of the AARRP (Applied Atmospheric Resources Research Program). The AARRP is a component of Thailand's national program of weather modification under the direction of the BRRAA (Bureau of Royal Rainmaking and Agricultural Aviation). Part I of this appendix focuses on the design and execution of the Thai, exploratory, randomized, cold cloud experiments and on the conceptual model that is guiding these investigations. The treatment units for these experiments are the convective cells which contain cloud towers that meet the liquid water and updraft requirements. In the Thai design, the cell receives the on-top AgI (silver iodide) treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells. The experimental unit consists of the small, multiple-cell convective system located within a radius of 25 kilometers and centered at the location of the convective cell that qualifies the unit for the first treatment. Evaluation of the experiments is to be accomplished using an S-band (10-centimeter) radar that is located near Omkoi in northwestern Thailand.

Fifteen experimental units (8 seed and 7 no seed) have been obtained to date, and they appear to be well-matched. No evidence so far indicates that deliberate or unintended bias has been a factor in the selection of these random cases and in the subsequent cloud treatments. Evaluation of these units and the convective cells contained within them is presented in part II of this appendix.

B.I.1 Historical Background

Since the late 1960s, scientific and technical organizations in the Kingdom of Thailand have been involved with a series of experiments and operational programs to increase rainfall through cloud seeding. This effort has taken place under the direction of His Majesty King Bhumibol Adulyadej. A national program of weather modification under the direction of the RRRDI (Royal Rainmaking Research Development Institute) was formalized in 1975.

Since program inception, RRRDI leadership has attempted to improve the effectiveness of their program by taking advantage of the latest scientific findings. In recent years, His Majesty the King recognized the need for the development and implementation of a more comprehensive scientific approach to the design, operation, and evaluation of Thailand's weather modification program. Therefore, the RTG (Royal Thai Government) requested assistance from the USAID (U.S. Agency for International Development), which agreed to sponsor a visit by a team of experts to assess the RRRDI program and make suggestions for improvements. This assessment, which was conducted under the auspices of the Bureau of Reclamation at the request of USAID, was made by four scientists who visited Thailand from September 7-26, 1986. Their assessment and recommendations are contained in a report entitled "Weather Modification Assessment: Kingdom of Thailand" (Silverman et al., 1986).

The report recommended a comprehensive 5-year developmental program to improve the technical capabilities of the RRRDI through training, additional equipment, and a demonstration cloud seeding project. These recommendations were accepted by USAID and a new, broadly-based program known as the AARRP was established.

Subsequent to the report by Silverman et al. (1986), a core training course was conducted in February and March 1988 to acquaint AARRP participants with the scientific principles, terminology, and technology of weather modification as a water augmentation tool. Simultaneous to and following this training, a number of studies were conducted in preparation for the demonstration cloud seeding project. These studies are described in a report by Medina et al. (1989).

The basic concepts to be tested in Thailand, involving either warm cloud seeding to increase the coalescence of liquid drops or cold cloud seeding to produce dynamic effects and increased rainfall, were investigated using a number of cloud models. The model runs indicated that both seeding approaches have potential for increasing rainfall in Thailand, and that perhaps 35 percent of the potential operational days might be suitable for seeding for dynamic effects.

Preliminary work on the demonstration design extended beyond the numerical studies of possible responses to seeding. After visiting potential experimental sites, RRRDI and Reclamation officials selected the southern part of the Bhumibol Catchment area of northwestern Thailand as the demonstration project location (fig. B.I.1). The Field Operations Center was located first (1991) at the Bhumibol Dam site and later (1992) moved to Chiang Mai Airport. A weather radar was installed in 1991 at a site about 9 kilometers southeast of Omkoi on a ridge (height 1,160 meters), which provides a good view of the southern catchment area drainage.

This paper concentrates on the initial results of the testing of dynamic cold cloud seeding concepts in Thailand. The design of the exploratory Thai experiments, their implementation, and first results are discussed to allow for comment from our scientific colleagues throughout the world. The sample is still too small for definitive conclusions.

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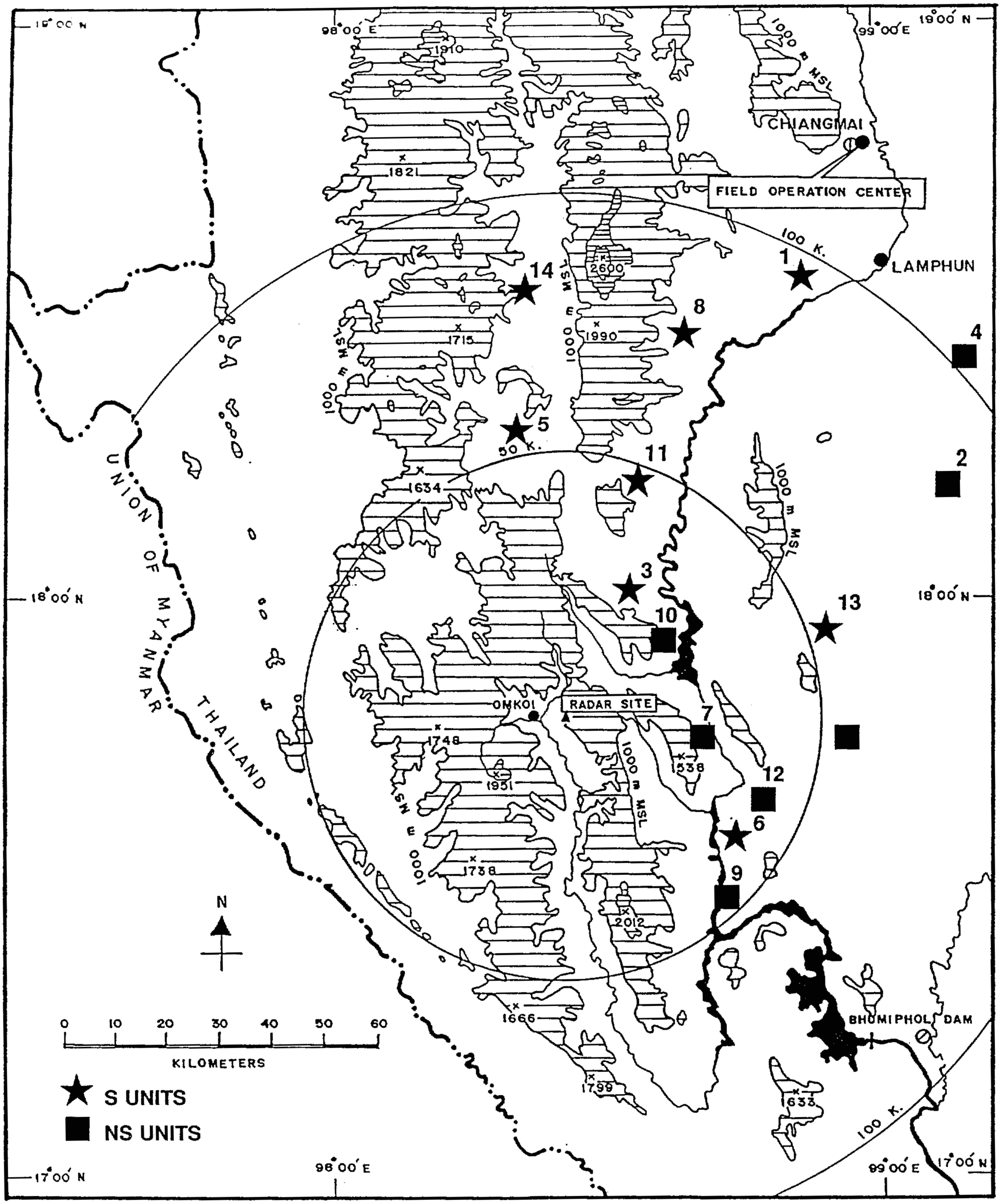

Figure B.I.1. - Map of the project area. The range rings (in kilometers) are relative to the AARRP radar. The locations of each experimental unit are plotted on the map as either squares (NS cases) or stars (S cases). The numbers identify the units in the order that they were qualified, beginning in 1991. See table B.I.1 for listing.

B.I.2 Summary of Results of Relevance to Thailand

The most systematic investigation of the potential of "dynamic seeding" for rainfall enhancement began in clouds over the Caribbean Sea in the mid-1960s (Simpson et al., 1967) and continued in Florida in the series of experiments that came to be called the FACE (Florida Area Cumulus Experiment). Although the FACE program did not provide conclusive proof that seeding had increased the areal precipitation, the estimated rainfall increases ranged between 10 and 25 percent for the target area covering 1.3 x 10^4 square kilometers and between 20 percent and 50 percent for groups of treated convective clouds within the target area (called the "floating target") (Woodley et al., 1982; 1983). The FACE program also provided strong evidence for substantial increases in rainfall from individual convective clouds and cells. The first experiment (in 1968 and 1970) indicated that the rainfall from individual clouds could be increased by over 100 percent (Simpson and Woodley, 1971).

A major breakthrough in the second of the two experiments (1978 to 1980) was made with the development of a sophisticated method to identify, track, and assess the properties of the treated clouds throughout their lifetimes. Use of this technique permitted a more comprehensive analysis of the effect of seeding on the individual convective cells. Again, the results indicate rain increases of over 100 percent (Gagin et al., 1986).

These results for tropical clouds in Florida provided the impetus for continuation of dynamic seeding research in Texas. The Texas research to date indicates that dynamic seeding has enhanced the rainfall from individual cells by over 100 percent, thereby replicating many of the Florida results. In addition, rain increases of 25 to 30 percent are indicated for the experimental unit (i.e., the small mesoscale convective cluster) that covers nearly 2,000 square kilometers (Rosenfeld and Woodley, 1989; 1993). This effort is continuing.

In summary, the scientific evidence from cloud seeding research programs in Florida and Texas that have employed dynamic seeding techniques indicates that rainfall can be increased from convective clouds by over 100 percent on the scale of individual cells, by 25 to 50 percent on the scale of groups of convective clouds, and by 10 to 25 percent over targets up to 13,000 square kilometers in size. The strength of the evidence for enhanced rainfall decreases, therefore, as the scale of the rainfall increases. The evidence is strongest for individual cells where the seeding signal is largest, and weakest for large target areas where the seeding signal is small.

B.I.3 The Dynamic Seeding Conceptual Model

The revised dynamic seeding conceptual model has been discussed recently by Rosenfeld and Woodley (1993). The main departure of the new dynamic seeding model from the "classical" model of the past (Woodley et al., 1982) is the realization that dynamic seeding can also produce a substantial increase in convective rainfall without a large increase in the maximum height of the seeded entity.

The steps in the new conceptual chain are supported by new and old scientific findings from a number of research projects. These findings have been combined with the new results to synthesize a revised conceptual model for dynamic seeding that in no way contradicts the precepts of the old, but merely builds and expands on them in places where physical insight was lacking.

Building on the conceptual models that guided the Florida and Texas experimentation suggests that seeding for dynamic effects operates to produce more rain from individual cells and groups of cells through the following steps that are illustrated on figure B.I.2:

NON-SEEDED STAGES

Cumulus Growth Stage

The freezing of supercooled rain drops plays a major role in the revised dynamic seeding conceptual model. Therefore, a suitable cloud has a warm base and a vigorous updraft that is strong enough to carry the rain drops which are formed in the updraft above the 0 °C isotherm level. Such a cloud has a vast reservoir of latent heat that is available to be tapped by natural processes or by seeding.

Supercooled Rain Stage

At this stage, a significant amount of supercooled cloud and rainwater exist between the 0 and the -10 °C levels, which is a potential energy source for future cloud growth.

A cloud with active warm rain processes but a weak updraft will lose most of the water from its upper regions in the form of rain before growing into the supercooled region. Therefore, only a small amount of water remains in the supercooled region for the conversion to ice. Such a cloud has no dynamic seeding potential.

The Cloud Top Rainout Stage

If the updraft is not strong enough to sustain the rain in the supercooled region until it freezes naturally, most of it will fall back toward the warmer parts of the cloud without freezing. The supercooled water that remains will ultimately glaciate. The falling rain will load the updraft and eventually suppress it, cutting off the supply of moisture and heat to the upper regions of the cloud, thus terminating its vertical growth. This occurrence is common in warm rain showers from cumulus clouds.

The Downdraft Stage

At this stage, the rain and its associated downdraft reach the surface, resulting in a short-lived rain shower and gust front.

The Dissipation Stage

The rain shower, downdraft, and convergence near the gust front weaken during this stage, lending no support for the continued growth of secondary clouds, which may have been triggered by the downdraft and its gust front.

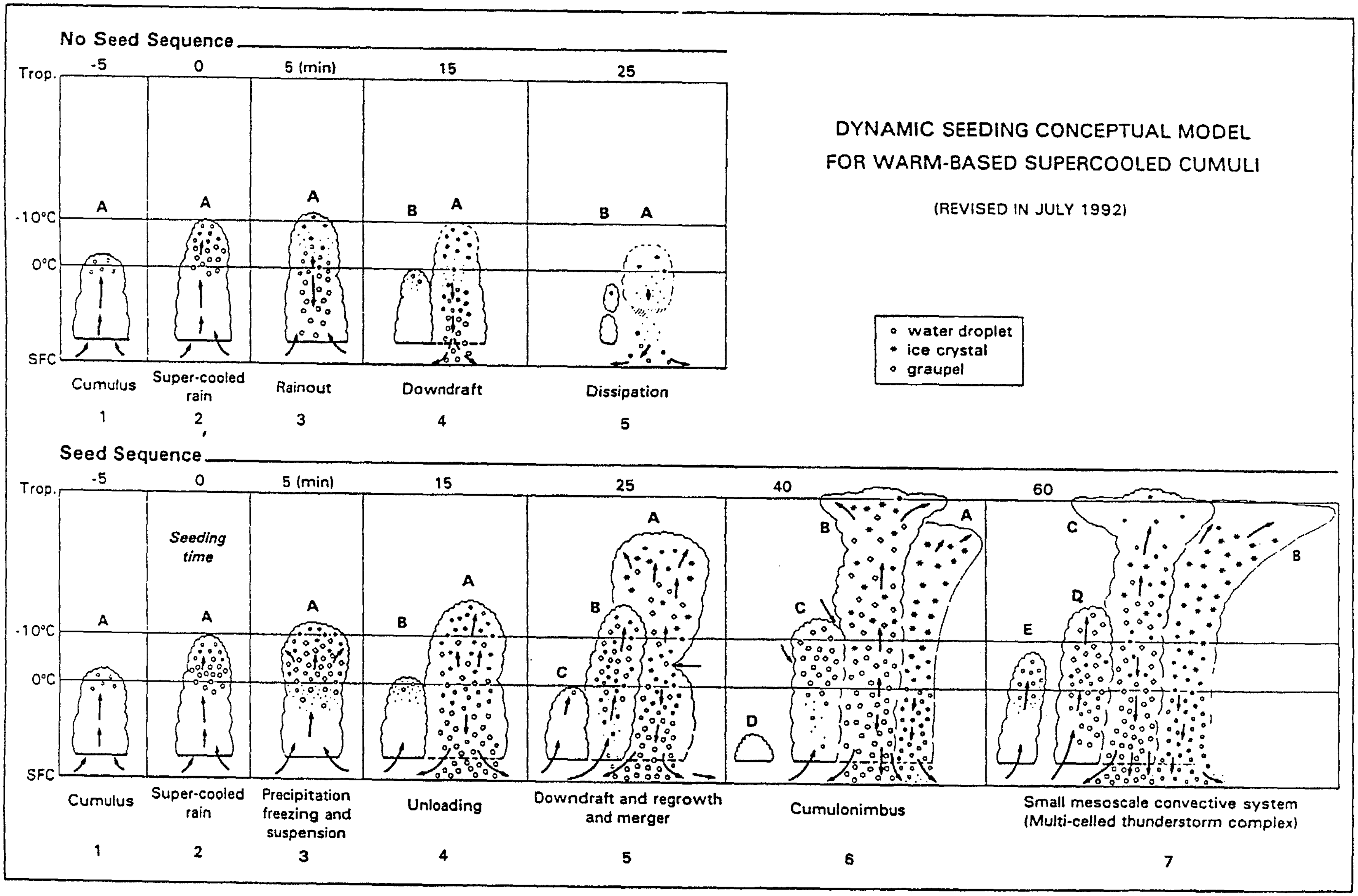

Figure B.I.2. - Diagrammatic illustration of the dynamic seeding conceptual model for warm based supercooled cumuli, revised as of July 1992.

SEEDED STAGES

The *Cumulus Growth* and the *Supercooled Rain* stages are the same for the seeded sequence as they are for natural processes.

The Glaciation Stage

The freezing of the supercooled rain and cloud water near the cloud top at this stage may occur either naturally or be induced artificially by glaciogenic seeding. This conceptual model is equally valid for both cases.

The required artificial glaciation is accomplished at this stage through intensive, on-top seeding of the updraft region of a vigorous, supercooled cloud tower using a glaciogenic agent (e.g., AgI). The seeding rapidly converts most of the supercooled water to ice during the cloud's growth phase. The initial effect is the formation of numerous small ice crystals and frozen rain drops.

This rapid conversion of water to ice releases the latent heat of fusion—faster and greater for the freezing of raindrops—which acts to increase tower buoyancy and updraft and, potentially, its top height. (The magnitude of the added buoyancy is modified by the depositional heating or cooling that may occur during the adjustment to ice saturation (Orville and Hubbard, 1973.) Entrainment is likely enhanced in conjunction with the invigorated cloud circulation.

The frozen water drops continue to grow as graupel as they accrete any remaining supercooled liquid water in the seeded volume and/or when they fall into regions of high supercooled liquid water content. These graupel particles will grow faster and stay aloft longer because their growth rate per unit mass is larger and their terminal fall velocity is smaller than water drops of comparable mass. This process will cause the tower to retain more precipitation mass in its upper portions. Some or all of the increased cloud buoyancy from seeding will be needed to overcome the increased precipitation load.

If the buoyancy cannot compensate for the increased loading, the cloud will be destroyed by the downdraft that contains the ice mass. The downdraft will be augmented further by cooling from the melting of the ice hydrometeors just below the freezing level.

The retention of the precipitation mass in the cloud's upper portions delays the formation of the precipitation-induced downdraft and the resultant disruption of the updraft circulation beneath the precipitation mass. This retention allows more time for the updraft to feed additional moisture into the growing cloud.

The Unloading Stage

The greater precipitation mass in the upper portion of the tower eventually moves downward, along with the evaporatively-cooled air that was entrained from the drier environment during the tower's growth phase. The descending precipitation suppress the updraft. If the invigorated pulse of convection has had increased residence time in regions of light to moderate wind shear, however, the precipitation-induced downdraft may form adjacent to the updraft, forming an enhanced updraft-downdraft couplet. This unloading of the updraft may allow the cloud a second surge of growth to cumulonimbus stature.

When the ice mass reaches the melting level, some of the heat released in the updraft during the glaciation process is reclaimed as cooling in the downdraft. This down rush of precipitation and cooled air enhance the downdraft and the resulting outflow beneath the tower.

The Downdraft and Merger Stage

The precipitation beneath the cloud tower is enhanced when the increased water mass reaches the surface. In addition, the enhancement of the downdraft increases the convergence at its gust front.

The Mature Cumulonimbus Stage

The enhanced convergence acts to stimulate more neighboring cloud growth, some of which will also produce precipitation, leading to an expansion of the cloud system and its conversion to a fully developed cumulonimbus system.

When this process is applied to one or more suitable towers residing within a convective cell as viewed by radar, greater cell area, duration, and rainfall are the result. Increased echo top height is a likely, but not necessary, outcome of the seeding, depending on how much of the seeding-induced buoyancy is needed to overcome the increased precipitation loading.

The Convective Complex Stage

When seeding is applied to towers within several neighboring cells, increased cell merging and growth will result, producing a small mesoscale convective system and greater overall rainfall. This sequence of events is idealized. Dissipation may follow the glaciation stage or any subsequent stage if the required conditions are not present.

It is important to note that the above model applies to convective clouds in which the coalescence process is active to produce rain drops in the supercooled region. The freezing of these raindrops produces the bulk of the fusion heat release (Lamb et al., 1981). A useful guideline for distinguishing between clouds that are likely to produce supercooled rain and those that will not, involving parcel buoyancy at 500 millibars and cloud-base temperature, is provided by Mather et al. (1986).

This conceptual model applies optimally to clouds having mean updrafts strong enough to carry the rainwater to temperatures where it can be nucleated artificially, but not having updrafts strong enough to carry the rainwater to heights where the temperature is cold enough for complete natural freezing. The updraft velocities should be at least comparable to the terminal fall velocity of the raindrops at that level (i.e., about 10 meters per second). Assuming that the rate of ascent of cloud top is half the peak updraft velocity, a minimum of 5 meters per second vertical growth rate is required for the cloud top while growing through the 0 to -10 °C levels. This requirement means that a suitable cloud must cover the 1600-meter vertical distance that normally exists between the 0 and -10 °C levels in 5 minutes at most.

To be effective, several seeding flares should be ejected into the updraft region to ensure that the freezing will be completed *before the updraft begins to wane*. Although one flare contains a sufficient number of ice nuclei to seed a typical updraft, there may not be enough time to disperse this material within the updraft during the short time (< 5 minutes) that the supercooled rainwater exists at the seeding level.

The consequences of seeding too late in the life cycle of a cloud is usually accelerated dissipation. This dissipation occurs when a mass of supercooled rainwater is glaciated artificially without an attendant updraft. The released heat, which is not sufficient to regenerate a significant updraft, remains aloft while the frozen precipitation continues downward. When this frozen precipitation eventually melts and cools the cloud, it destroys the updraft and/or enhances the downdraft, resulting in the destruction of the cloud.

It must be emphasized that artificial seeding merely imitates a natural process, which is often the mechanism that transforms cumulus convection to cumulonimbus convection. Seeding is most effective, however, when this transformation is unable to proceed naturally. Therefore, seeding tests must be conducted during these marginal conditions, and not when deep, vigorous, natural cumulonimbi are prevalent.

This rather complex conceptual model is backed by observations that taller convective cells precipitate more. Observations of natural convective rain clouds in Florida (Gagin et al., 1985) and in Texas (Rosenfeld and Woodley, 1989) indicate that an increase of cell top height by 20 percent nearly doubles its rain production. If a seeding-induced enlarged cloud behaves as a natural cloud reaching the same top height, the rainfall from the treated cloud will be increased accordingly. This increase was nearly the case in two Florida studies (Simpson and Woodley, 1971; Gagin et al., 1986), where 20-percent increases in mean cell height explained about 70 percent of the factor of 2.60 seeding effect on the rainfall.

This increase has not been the case in Texas, however, where it now appears that more than a doubling of the rainfall has been associated with only about a 7-percent increase in mean maximum cell height. This finding, in conjunction with the evidence that seeded clouds in Texas produce more rainfall than unseeded clouds of the same height, suggests that additional physical processes are at work in enhancing the rainfall by seeding. These processes have been addressed in the new model.

The revised conceptual model is different from the original model in several important respects. It was assumed implicitly in the early model that the AgI treatment would produce high concentrations of very small ice crystals and, in effect, "overseed" (i.e., too many nuclei for the available water supply) portions of the treated volume, resulting in less efficient precipitation processes. This possible outcome was viewed "as a small price to pay" in exchange for the release of fusion heat that would lead eventually to a larger, longer-lasting cloud in which natural precipitation processes would dominate.

More recent thinking, however, suggests that this "over-seeding" concept may not be valid in vigorous warm-based clouds (Rokicki and Young, 1978). A large amount of supercooled water normally exists at the seeding level in such clouds. Although seeding produces an obvious glaciation signature (Sax et al., 1979), an extensive overseeded region is rarely encountered. The normal circumstance in cloud immediately following seeding is a mix of cloud water, seeding-induced ice crystals, and raindrops, a situation that should be conducive to the formation of graupel through the aerodynamic capture of the ice crystals by the raindrops, which then freeze (Lamb et al., 1981). Under such circumstances, much of the cloud's water mass may be intercepted before it can be evacuated in the anvil.

Once the enhanced graupel mass exists, Johnson (1987) indicates that the graupel will fall slower and grow faster than water drops of comparable mass. This slow descent means that the seeding-induced graupel will reside in the cloud tower longer and achieve greater size than a population of water drops within a similar unseeded cloud.

This effect is consistent with the increased reflectivity aloft after seeding, accompanied by some decrease of reflectivities at lower levels. This area of larger reflectivity reaches cloud base as additional rainfall about 40 minutes after initial seeding. Bruintjes et al. (1992) have also noted increases in the reflectivities aloft after seeding clouds in South Africa, which they attributed to the same effect of conversion from rain to graupel, as suggested by Johnson (1987).

The increased precipitation loading in the seeded tower will require greater cloud buoyancy and a stronger updraft to keep it aloft. Therefore, some of the increased buoyancy in Texas clouds may be expended in carrying the larger precipitation load, leaving little buoyancy left over for the production of higher cloud tops. In Florida, however, the fusion heat releases should be higher because of higher rainwater contents. This additional rainwater may allow seeded Florida clouds to carry the increased precipitation load and still have enough buoyancy left for additional vertical cloud growth. Only with numerical cloud modeling with explicit microphysics will it be known for sure.

The retention of the increased ice mass high in the cloud is an important new aspect of the dynamic seeding conceptual model that may help explain how an effect of seeding is communicated immediately to the rest of the cloud. The downdraft is delayed if the precipitation mass can be held aloft as a result of the seeding. This delay provides additional time for the growth of the cloud tower. Only until this precipitation mass begins to move downward is the updraft in jeopardy. Under conditions of vertical wind shear, the precipitation may fall adjacent to the parent updraft and not disrupt it. In addition, the decreased precipitation loading in the cloud tower that formerly contained the water mass may allow it to renew its growth to greater heights, possibly reaching cumulonimbus stature. This second surge of growth is a common phenomenon in natural clouds, especially in the tropics where warm rain processes are most active. Seeding may also produce this second surge of growth in clouds that could not have done so naturally.

Downdrafts are vitally important to the development of a cloud system, which is why the dynamic seeding conceptual model incorporates the ideas of Simpson (1980) regarding the role of the downdraft following seeding. However, the downdraft probably cannot explain the explosive initial growth of the seeded tower that sometimes occurs following seeding because this growth often occurs prior to or simultaneous with the rain reaching the ground.

Evidence in support of the portion of the conceptual model dealing with increased cloud growth, greater cloud duration, more mergers, and additional rainfall has been presented earlier by Rosenfeld and Woodley, 1989; 1993). The observational evidence to date clearly supports these links in the conceptual chain.

B.I.4 Design of the Thai Cold Cloud Experiments

B.I.4.1 Aircraft and radar systems

An AeroCommander 690B turbo-prop aircraft was provided to the RRRDI and its AARRP effort under lease from Thai Flying Service. This turbo-prop aircraft was equipped with an airborne data acquisition and seeding system and served as the program cloud physics platform and seeder. In addition to standard avionics and flight instrumentation, the AeroCommander was equipped with the following: a Johnson-Williams-type liquid water content meter manufactured by Cloud Technology, Inc., a thermo-electric dew point hygrometer, a reverse flow thermometer, a Ball variometer, and a satellite-based GPS navigation system that permits location of the aircraft to within 100 meters. A forward-looking nose video camera was mounted in the cockpit and provided a continuous view of cloud conditions during flight through the extreme right side of the windshield.

The GPS navigation system was a major addition to the standard aircraft navigation systems (e.g., VOR/DME, LORAN, etc.) because of its increased position accuracies. This accuracy allowed highly accurate location of each treatment position relative to the radar echoes during the operational and evaluation phases of the experiment.

The liquid water hot wire and the Ball variometer were configured to measure water contents and draft speeds up to 6.0 grams per cubic meter and 2,000 feet per minute, respectively. No Thai cloud had water contents approaching 6.0 grams per cubic meter, so this threshold was never exceeded. Many Thai clouds did, however, have drafts exceeding 2,000 feet per minute, particularly during pre-monsoon conditions, so the measured maxima and the calculated mean maxima are underestimates of the true values.

The main operational and research radar for the AARRP effort is an EEC (Enterprise Electronics Corporation) Model DWSR-88S S-band (10-centimeter) Doppler Weather Surveillance Radar with a 1.2° conical beam. The AARRP radar is situated on a hill 9 kilometers southeast of Omkoi (17° 47'54"N; 98° 25'57"E) at an elevation of 1,160 meters. The surrounding terrain is below 1° elevation except between 225° and 275° azimuth, where one hill top extends up to 2.3° elevation. During the program, the radar was operated 24 hours per day in either the surveillance or volume-scan modes.

B.I.4.2 Design

The Thai experiments were carried out in accordance with the Design Document and AARRP Operations Plans by Woodley et al. (1991). In every case, the experimental unit was the small multiple-cell convective system within a circle having a radius of 25 kilometers and centered at the location of the convective cell which qualified the unit for treatment. The treatment decisions were randomized on a unit-by-unit basis and all suitable convective cells within the unit received the same treatment—AgI (silver iodide) in the case of an S (seed) decision or simulated AgI in the case of an NS (no seed) decision.

The selection of the experimental unit was based upon the following requirements:

1. A preliminary sampling pass shall establish that convective cells in the area contain maximum (1-second values) liquid water contents of at least 1.0 gram per cubic meter and maximum (1-second values) updrafts of at least 1,000 feet per minute (i.e., ≥ 5 meters per second), as determined from real-time readouts aboard the aircraft.

2. The experimental unit shall consist of the small multiple-cell convective system located within a radius of 25 kilometers and centered at the location of the convective cell which qualified the unit for the first treatment.

3. No cloud or cell within the experimental unit at the time of initial treatment shall have a top reaching above 10 kilometers a.g.l.

4. At least some of the subject cells shall have top temperatures of -10 °C or colder.

5. At the time of selection, the center of the experimental unit shall be at least 40 kilometers from cumulonimbus clouds displaying radar reflectivities of 50 dBZ or greater in the vicinity.

During the experimentation on a particular experimental unit, the following requirements applied:

1. The center of the experimental unit shall always be at the location of the convective cell during the qualification pass of the aircraft. This position is advected with time with the mean direction and speed of the convective cells.

2. All untreated cells contained entirely within the 25-kilometer circle become potential seeding targets and, by definition, become a part of the experimental unit.

In the Thai design, therefore, the treatment units are the convective cells which contained cloud towers that met the liquid water and updraft requirements. The cell receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells.

Prior to commencement of the 1993 experiments, a decision was made to allow for relaxation of the stringent requirements for qualification of an experiment. Specifically, the 1.0-gram-per-cubic-meter requirement was relaxed to 0.5 gram per cubic meter, and the requirement that no cell within the unit shall have an echo top exceeding 10 kilometers was eliminated, as was the 40-kilometer separation distance between the center of the prospective unit and nearby 50-dBZ cores. This decision was made in the hope of qualifying more units with the intention of stratifying them later during the analysis phase.

During the actual experimentation, however, the flight scientists "attempted to play by the old rules." As best can be determined, all units were qualified by the old protocol with no loss in unit qualifications as a consequence of adhering to the old qualification rules.

The randomized seeding instructions for the single-cell experiment were prepared by the Bureau of Reclamation in Denver, Colorado, U.S. In 1991, the blocking of the randomization was based on the time that the first cumulonimbus echo in Thailand having a top exceeding 10 kilometers formed within 159 kilometers of the radar. Three blocks were used:

1. Block 1 - Used on days when the first Cb echo forms in the study area prior to 1300 LST.

2. Block 2 - Used on days when the first Cb echo forms in the study area after 1300 LST, but before request for a treatment decision.

3. Block 3 - Used on days when no Cb echo has formed in the study area prior to request for a treatment decision.

This blocking scheme was developed to account for the fact that the weather is distinctly different on days with early deep convection from days on which deep convection is delayed until late in the day.

By 1993, however, the view prevailed that the blocked randomization was too complex for the initial Thai experiments. A new set of randomized instructions without blocking was prepared and used in the 1993 experiments. Thus, only 1 experimental unit was qualified with the blocked scheme, and 14 were qualified with the simple randomization.

The nucleant that was used in this experiment was 20-gram AgI flares having the EJ-20 formulation and manufactured by Atmospherics Inc., in Fresno, California, U.S. This flare is complexed with chlorinated hydrophilic material that allows it to nucleate at a faster rate than the modified TB-1 formulation that has been used in Texas. According to tests at the Cloud Simulation and Aerosol Laboratory at Colorado State University, the EJ-20 and the modified TB-1 flares produce about 3×10^{14} and 8×10^{14} ice crystals per gram of AgI, respectively, at -10 °C. Both flares yield about 10^{13} ice crystals per gram of AgI at -5 °C.

The flares were ejected at the seeding flight altitude (normally 21,500 feet) from the project AeroCommander 690B turbo-prop aircraft. When ejected at seeding altitude, each flare normally burns for at least 50 seconds and falls more than 1.5 kilometers in still air. The actual fall distances were likely less because the flares normally were dropped into vigorous updrafts. The seeder aircraft carried a maximum of 200 20-gram flares on each flight.

B.I.5 Experimental Procedures

During the randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical top heights of 6.0 to 7.0 kilometers and top temperatures of -7 to -9 °C). Between 1 and 10 flares normally were ejected during a seeding passe. The flare ejection button was pressed about every second while the cloud liquid water reading was greater than 0.5 gram per cubic meter and the aircraft was in updraft (the 1.0-gram-per-cubic-meter and 5-meter-per-second requirements applied only to the initial qualification pass). In some cases, seeding or simulated seeding was done 1,000 feet or less over the top of an especially vigorous hard tower when previous cloud passes on a particular day had established the suitability of the subject clouds. In the simulated seeding passes, no flares were actually ejected when the button was pressed, but the event was still recorded in the aircraft data system by activating an event switch.

The treatment decision for each experimental unit was revealed after the qualification pass to maximize the learning experience of the Thai scientists and to avoid the extra costs that would have been incurred through the use of placebo flares. This decision is not without its risks, however, because knowledge of the treatment decision could result in inadvertent bias either in the conduct of a given experiment and/or in the selection of the next experimental unit. This potential problem is discussed in more detail in the next section.

Once the decision on a particular unit had been made, it was irrevocable and could not be changed, nor could the unit be eliminated from the sample. Only failure of the radar can result in elimination of a unit from the sample. Without the radar, no rainfall data will be available to evaluate the unit.

During the operations, the pilots and flight scientists attempted to make certain that all seeding or simulated seeding passes took place within the confines of the experimental unit (i.e., within 25 kilometers of the qualification point). The "cloud pointer" on the aircraft was used to mark the position of the qualification pass, and this pointer was used to keep the aircraft within the unit. As the unit moved, however, the flight scientist sought a new center position from the radar operator, who was plotting the unit on the radar display and moving it along with the motion evident in the radar echoes nearby. This position was then used to update the pointer aboard the aircraft.

Regardless of the treatment decision, the flight patterns were essentially the same. The object was to recognize what nature was trying to do with a particular cloud or cloud group and then seeding to enhance the natural tendencies. This enhancement usually required multiple passes through suitable young towers growing on the upshear flanks of the parent cloud, and the ejection or simulated ejection of about 1 AgI flare per second while in suitable conditions.

Doing the seeding within young vigorous clouds as they moved through the treatment level required teamwork between the flight scientist and the pilots. Care was taken not to fly into mature large clouds that could have beaten up the aircraft and were not suitable for seeding in any case. This care generally meant that young upshear towers were worked at angles to the shear vector so that the large cloud, which was normally downshear, was not penetrated. The echo cores could be located on the aircraft radar. Most cloud towers more than 5,000 feet above the aircraft already had echo cores and were unsuitable. Flight patterns requiring a 90° left turn and then a 270° degree right turn (or vice versa) frequently were helpful, as were race-track patterns that permitted visual monitoring of the cloud on one of the legs of the racetrack and repenetration of suitable towers and seeding on the other. Sometimes, no set patterns were possible because of intervening cloud clutter, and the aircraft was flown in whatever way that was necessary to get the job done.

A good unit was one that had a treatment duration of at least 1 hour following qualification and had 20 to 30 seeding passes, which resulted in the ejection or simulated ejection of 100 or more AgI flares. These conditions could not always be controlled, however, and one was left to make the best of a particular situation.

Seeding continued in the unit as long as suitable towers were present, regardless of the treatment decision. The duration of seeding and the amount of nucleant that was expended in each experimental unit was unlimited. Treatment continued as long as cloud conditions were suitable. Treatment was terminated in a few cases when the aircraft ran out of fuel and/or the experimental unit moved beyond 159 kilometers from the radar.

B.I.6 Operational Summary

One experimental unit was qualified in 1991 and 14 experimental units were qualified in 1993, for a total of 8 S and 7 NS units. Information for these cases is provided in table B.I.1, and a plot of their locations is provided on figure B.I.1. Further details are provided by Woodley and Rosenfeld (1993), including a listing of selected data for each cloud pass, a journal or diary for each random case, and mean pass data and a frequency plot of measured pass distances for each day of randomized experimentation.

Table B.I.1. - Summary of randomized cases.

Date	Cloud Base Temp (°C)	Time of Qual. Pass (LST)	Position of Qual. Pass (Lat.; Long)	Treatment Decision (S or NS)	# of Flares Fired	# of Treated Towers	Time of 1st Treatment (LST)	Time of Last Treatment (LST)	Treatment Duration (min)
08/07/91	22	15:34	18 34.8;98 51.6	S	29 (29)	13	15:40	17:11	92
04/15/93	18	14:53	17 59.8;99 16.7	NS	45 (0)	9	15:04	15:46	42
04/18	11	15:41	17 55.7;98 36.7	S	57 (57)	12	15:45	16:33	48
04/20	15	15:19	18 13.6;99 17.3	NS	79 (0)	13	15:30	16:36	66
04/21	15	13:59	18 16.8;98 21.0	S	112(112)	18	14:04	16:10	126
04/22	18	15:40	17 34.2;98 44.3	S	70 (70)	13	15:47	17:11	84
04/23	18	14:20	17 45.0;98 41.0	NS	91 (0)	17	14:27	16:19	112
04/25	16	14:45	18 27.4;98 36.2	S	118(118)	25	14:56	17:32	160
04/29	19	15:18	17 28.6;98 41.5	NS	96 (0)	17	14:26	15:50	84
05/04	22	15:17	17 52.0;98 40.2	NS	57 (0)	17	14:30	17:11	101
05/07	21	13:52	18 09.9;98 34.0	S	77 (77)	18	14:02	15:46	104
05/08	15	14:50	17 38.3;98 44.7	NS	89 (0)	18	14:59	17:20	141
05/09	18	14:26	17 50.6;98 56.8	S	156(156)	29	14:34	17:26	172
05/27	22	14:36	18 30.8;98 18.8	S	124(124)	25	14:47	17:15	148
06/04	21	15:08	17 41.7;98 57.4	NS	124 (0)	22	15:13	17:42	129

Note: 1. In the "# of Flares Fired" column, the first number for the seed cases is the number of flares attempted, and the second number in parentheses is the number of flares actually fired.
2. For the seed cases, all of the flares did fire—a remarkable performance for the seeding system.
3. For the no seed cases, the first number refers to the number of times that a toggle switch was activated to simulate seeding. Each activation was recorded by the data system. The second number in parentheses is zero (0) because no actual seeding was done and no flares left the rack.

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Although the Operations Plan allowed for relaxation of the qualification criteria that had been observed in 1991, it did not prove necessary. Only on April 21 was a unit qualified with an SLWC (supercooled liquid water content) < 1.0 gram per cubic meter. The qualification value was 0.74 gram per cubic meter. However, the threshold value of 1.0 gram per cubic meter had been exceeded on two of the three prior passes. Some uncertainty also exists concerning the accuracy of the SLWC measurements on this day, because the hot wire probe failed entirely three passes after the qualification pass. Other than this apparent violation of the old qualification criteria, no others are known as of this writing. However, one cloud in the experimental unit of May 9, 1993, may have exceeded 10 kilometers on its southern boundary for about 5 minutes around the time of the qualification pass.

Potential bias in the conduct and evaluation of a cloud seeding experiment should be evaluated wherever possible. It is important, therefore, to determine whether bias may have played some role in the Thai cold cloud seeding experiments. At this point, no evidence exists to indicate that deliberate or unintended bias has been a factor in the selection of the random cases, at least for the qualification pass, as can be seen in table B.I.2, for which maximum SLWC and updraft have been listed.

A second concern is whether the conduct of the experiment might have been biased after the treatment decision had been revealed. This possibility is more difficult to investigate because the effect of seeding itself may be a confounding factor. For example, the mean number of AgI flares expended and simulated in S and NS units were 93 and 83, respectively. The corresponding mean treatment durations (i.e., time of last treatment minus time of first treatment) were 117 minutes and 96 minutes, respectively. Are these flare expenditure and treatment duration differences indicative of a bias in the conduct of the experiment, or do they indicate that the AgI-treated clouds last longer and provide more seeding opportunities?

Listed in table B.I.3 are the durations of echoes within each experimental unit after the qualification pass, obtained from the set of radar analyses to be discussed later. Note that the 8 S units lasted 39 minutes longer on radar than the NS units. When the longest duration unit is eliminated from both the S and NS samples as a sensitivity test, the S versus NS disparity increases to 56 minutes, indicating that the S systems lived longer and, thereby, provided more seeding opportunities. Although this result could have occurred by chance, it is consistent with an effect of seeding.

Looking further at the question of bias, the mean number of treatment passes per day are 19 and 16 for the S and NS cases, respectively. This finding is consistent, of course, with the longer treatment durations for the S cases. Some might still view it as an indication of bias. It is interesting, however, that the treatment rate (i.e., number of AgI or simulated AgI flares per pass) is virtually identical for the two treatment categories—4.9 flares per pass for the S cases and 5.2 flares per pass for the NS cases.

B.I.7 Summary and Conclusions

The Thai cold cloud experiments have gone very well to date. The clouds are highly suitable microphysically for glaciogenic seeding intervention, and they appear to be responsive to seeding as is described in appendix B, part II. The experimental design has been implemented without problem. Its great similarity to that for the Texas experiments (Rosenfeld and Woodley, 1993) will allow comparison of the results for both regions. This comparison is illustrated in appendix B, part II. Such an interactive process should enhance the learning experience for the scientists involved in both projects.

Table B.I.2.- Listing of SLWC and updraft values for the qualification passes.

	Seed Cases			No Seed Cases	
Date	Max SLWC (gm/m^3)	Max Updraft (ft/min)	Date	Max SLWC (gm/m^3)	Max Updraft (ft/min)
08/07/91	3.57	1300			
04/18	3.05	1100	04/15	1.89	2000+
04/21	0.74	1900	04/20	1.36	2000+
04/22	1.43	2000+	04/23	1.43	1400
04/25	1.47	2000+	04/29	1.61	2000+
05/07	1.17	2000+	05/04	1.07	2000+
05/09	1.20	1900	05/08	3.53	2000+
05/27	1.22	1600	06/04	1.45	1300
Avg.	1.73	1725		1.77	1866

Table B.I.3.- Listing of the echo durations within the experimental units after the qualification pass.

	Seed Cases			No Seed Cases	
Time of No Echo	Qual. Time	Duration (min)	Time of No Echo	Qual. Time	Duration (min)
2130	1534	356			
1715	1453	97	1650	1453	117
1900	1359	301	1710	1519	111
1955	1540	255	1750	1420	220
1715	1445	150	1901	1518	223
1820	1352	268	1740	1517	143
2031	1426	249	1715	1450	145
1728	1447	199	2155	1508	407
Means		234			195

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PART II: RESULTS OF CLOUD-MICROPHYSICAL AND RADAR ANALYSES

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ABSTRACT

Part II provides the results of analyses of cloud-microphysical and radar data obtained in the context of Thailand's randomized, exploratory, cold cloud seeding effort that was discussed in part I. The sample is small and caution should be exercised in interpreting the results of these analyses.

Analyses of observations of cloud water contents, updrafts, and cloud-tower sizes obtained during the course of the randomized seeding experimentation in Thailand are presented as time composites relative to the point in the cloud pass where either the supercooled cloud liquid water content or the updraft reached its maximum 1-second value. Average maximum 1-second values of supercooled cloud liquid water content and updraft for the 190 aircraft passes on days with an experimental unit receiving AgI treatment are 1.28 grams per cubic meter and 5.1 meters per second, respectively. Corresponding values for the 130 aircraft passes on days with an experimental unit receiving simulated AgI treatment are 1.32 grams per cubic meter and 5.3 meters per second, respectively.

A total of 151 convective cells (87 seeded and 64 nonseeded) have been identified within the experimental units, and their properties have been computed through analysis of three-dimensional, volume-scan, S-band radar data using cell tracking software. The results indicate that AgI seeding may have increased the maximum cell areas by 25 percent, durations by 14 percent, and rain volumes by 69 percent. Little effect is indicated on maximum cell heights, which may be caused in part by underestimation of the glaciated tops of AgI-treated clouds by the S-band radar. Additionally, within the height range of 7 to 11 kilometers, seeded cells of a given maximum echo top produced more rain volume than unseeded cells of the same height. None of the results have strong statistical support.

Partitioning by cloud base temperature increased the apparent effect of seeding to 71 percent, 33 percent, and 125 percent for cell areas, durations, and rain volumes, respectively, within the warm base (temperature > 16 °C) partition. The apparent effect on maximum cell height is about +6 percent.

The results for the small sample (i.e., 7 S and 7 NS) of experimental units also show more S than NS rainfall. All results are comparable to what has been reported by the first two authors for a similar program in Texas, and are discussed in the context of the conceptual model guiding both experiments.

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B.II.1 Introduction

Part I presented the historical and conceptual framework for the exploratory randomized cold cloud seeding experiments in Thailand. This presentation was followed by a discussion of the design and the procedures that were implemented for this experiment and a description of the aircraft and radar systems that were available to the effort. The operational summary then provided the context for the analyses of the microphysical and radar data that are discussed in this paper. The sample is obviously quite small, which complicates the search for evidence of effects of AgI treatment. Nevertheless, past experience elsewhere suggests that inference of seeding effects might be possible despite the limited sample.

The philosophy or approach to the analyses for seeding effects and their interpretation has the following components:

1. The results cannot depend on the approach to the analyses.

2. Statistically significant results should be evident ultimately if the sample is large enough and if some method is found to account for the natural variability.

3. Seeding effects should be indicated in most of the analyses, even when no individual indication is statistically significant.

4. The results should be consistent with the conceptual model, or, if not, should suggest a plausible alternative explanation of the results.

5. The outcomes should agree with the findings in similar experimentation conducted elsewhere, especially that in Florida and Texas where the conceptual model and the design and its implementation are comparable to what has been done in Thailand.

In essence, therefore, the analysis process must not boil down to an exercise in statistics. All results must be plausible, reasonable, and physically consistent if they are to be believed.

B.II.2 The Cloud Microphysical Analyses

B.II.2.1 Procedures

Beginning on April 15 and continuing through June 6, 1993, flights of the AeroCommander aircraft were made through visually suitable clouds at temperatures ranging between -7 and -11° C, in order to access their internal characteristics. At issue was the SLWC in small drops (i.e., < 50 micrometers in diameter) as a function of the breadth and intensity of updrafts and downdrafts at the level of treatment. Although even greater interest exists in the SLWC content in larger drops, no means existed on the AeroCommander for measuring such drops. Following each flight, the recorded data were processed to provide the times and locations of each cloud, the ambient temperature and dew point, and the internal cloud temperatures, drafts, and water contents. Pass times were converted to pass distances by multiplying by the aircraft true airspeed. In those instances when the aircraft passed through the center of the cloud bubble top—determined from viewing the video tape from the aircraft nose camera—the pass distance corresponds to a cloud diameter.

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Three cautions are urged before considering the results. First, the draft measurements are reliable only to the extent that the pilots flew the AeroCommander at a constant, level attitude, and let the aircraft float with the draft. Any departure from this flight procedure, such as lowering the nose of the aircraft in an updraft, obviously would invalidate the estimates of draft speeds using the Ball Variometer. Second, the liquid water hot wire device failed on portions of April 20 and 21 when the deicing heater was not working properly. Third, the measurements are not from a random sample of clouds. Only the most vigorous clouds commensurate with flight safety were sought out and treated because the seeding methodology applies only to vigorous, supercooled clouds.

B.II.2.2 Results

Plots of mean SLWC and updraft relative to the point in the cloud where the SLWC is greatest (at $t = 0$) are presented on figures B.II.1 and B.II.2 for the S and NS days of randomized experimentation. Each plot is divided into new growth and old growth directions based on visual inspection of the clouds and the path that the aircraft took relative to these regions during penetration. The new growth region is commonly the upshear side of the cloud and the old growth is downshear. The third line in each plot represents the number of passes in the sample. There were 190 passes on days with S (seed) units and 130 passes on days with NS (no seed) units.

The plots on figures B.II.1 and B.II.2 are quite similar in appearance. The average peak SLWC values for the S and NS cases within 10 seconds upshear and downshear of the SLWC maximum are 1.28 grams per cubic meter and 1.32 grams per cubic meter, respectively. The updraft plots are rather flat in this interval.

Comparable plots using the maximum updraft as a reference are provided on figures B.II.3 and B.II.4. Note that the mean maximum updrafts for the S and NS samples are 5.1 and 5.6 meters per second respectively.

No obvious bias is evident in the microphysical plots for days with S and NS units. The plots of SLWC and updraft for the sample of days with NS units suggest that the clouds were only slightly wetter and more vigorous than the clouds on days with S units.

Finally, frequency plots of "half-pass" distances during aircraft penetration of the clouds during the randomized cases are presented for all cases together (fig. B.II.5), for just the S cases (fig. B.II.6) and for just the NS cases (fig. B.II.7). The plotted pass distances have been divided by two in order to approximate cloud radius. This approximation is good in instances when the aircraft penetrated the bubble cloud top near its center. Each bar represents the number of "half-pass" distances within the interval shown.

In examining figure B.II.5, it is obvious that most of the cloud passes had half-distances of less than 1400 meters. The plot itself has the appearance of a log-normal distribution. The S (fig. B.II.6) and NS plots (fig. B.II.7) are similar, but, as mentioned in part I, more passes took place on days with an S unit. The S cases also appear to have a longer tail toward larger cloud radii.

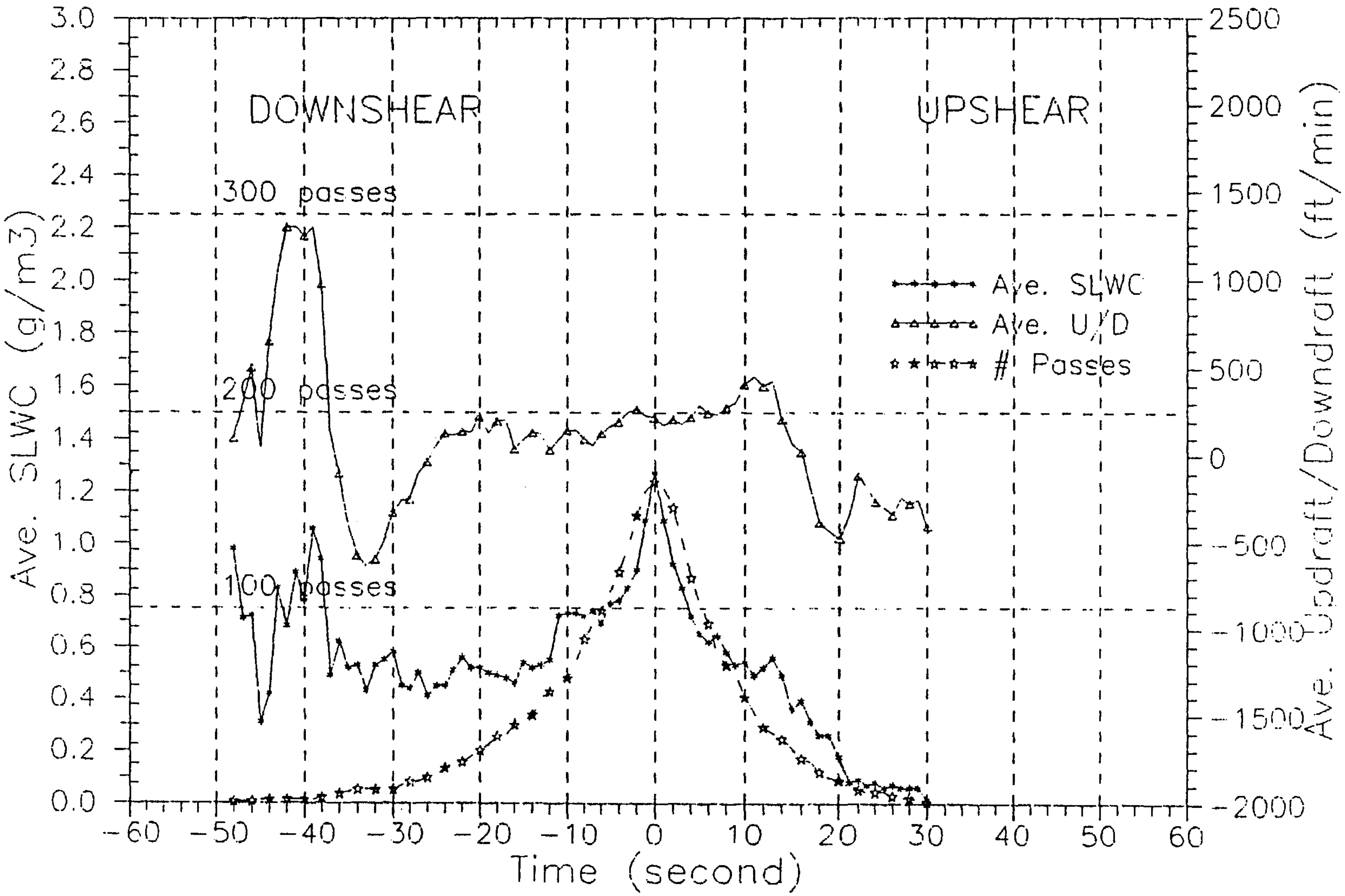

Figure B.II.1. - Plot of mean SLWC and updraft relative to the point in the cloud where the SLWC reached the highest pass value for all cloud penetrations on days with S units in 1993. The third line corresponds to the number of cloud passes as a function of time. The plot is divided into upshear and downshear directions.

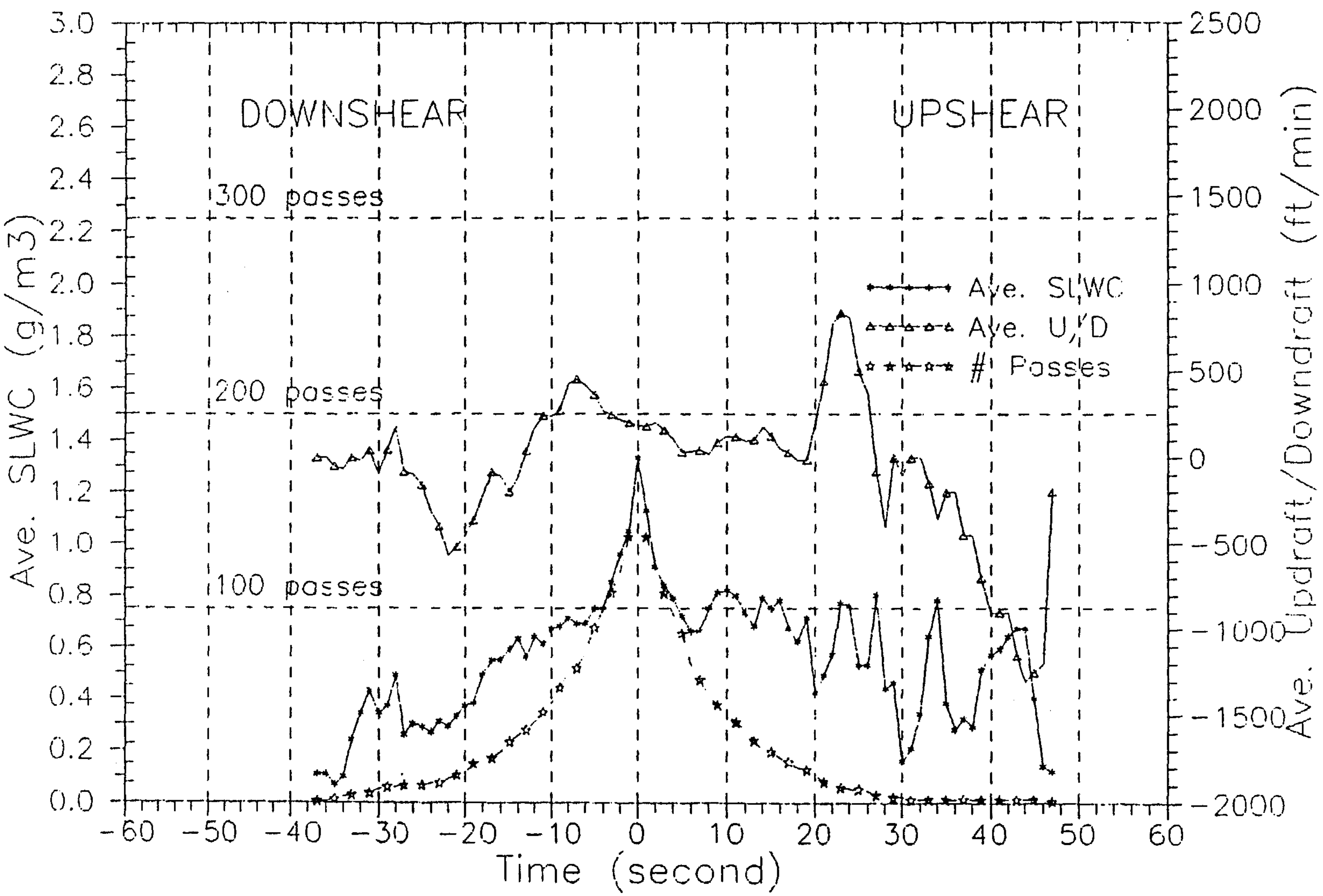

Figure B.II.2. - Plot of mean SLWC and updraft relative to the point in the cloud where the SLWC reached the highest pass value for all cloud penetrations on days with NS units in 1993. The third line corresponds to the number of cloud passes as a function of time. The plot is divided into upshear and downshear directions.

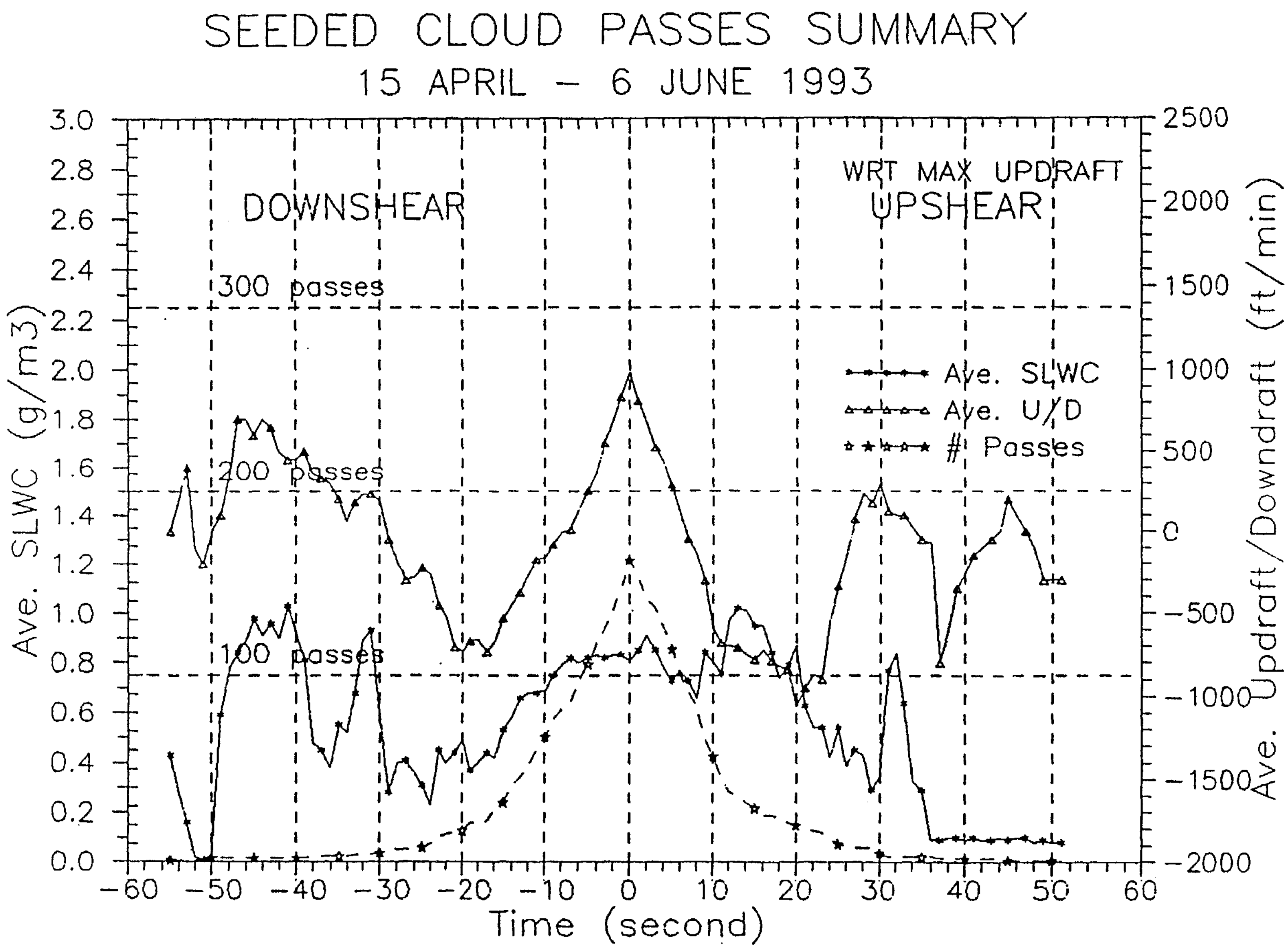

Figure B.II.3. - Plot of mean SLWC and updraft relative to the point in the cloud where the updraft reached the highest pass value for all cloud penetrations on days with S units in 1993. The third line corresponds to the number of cloud passes as a function of time. The plot is divided into upshear and downshear directions.

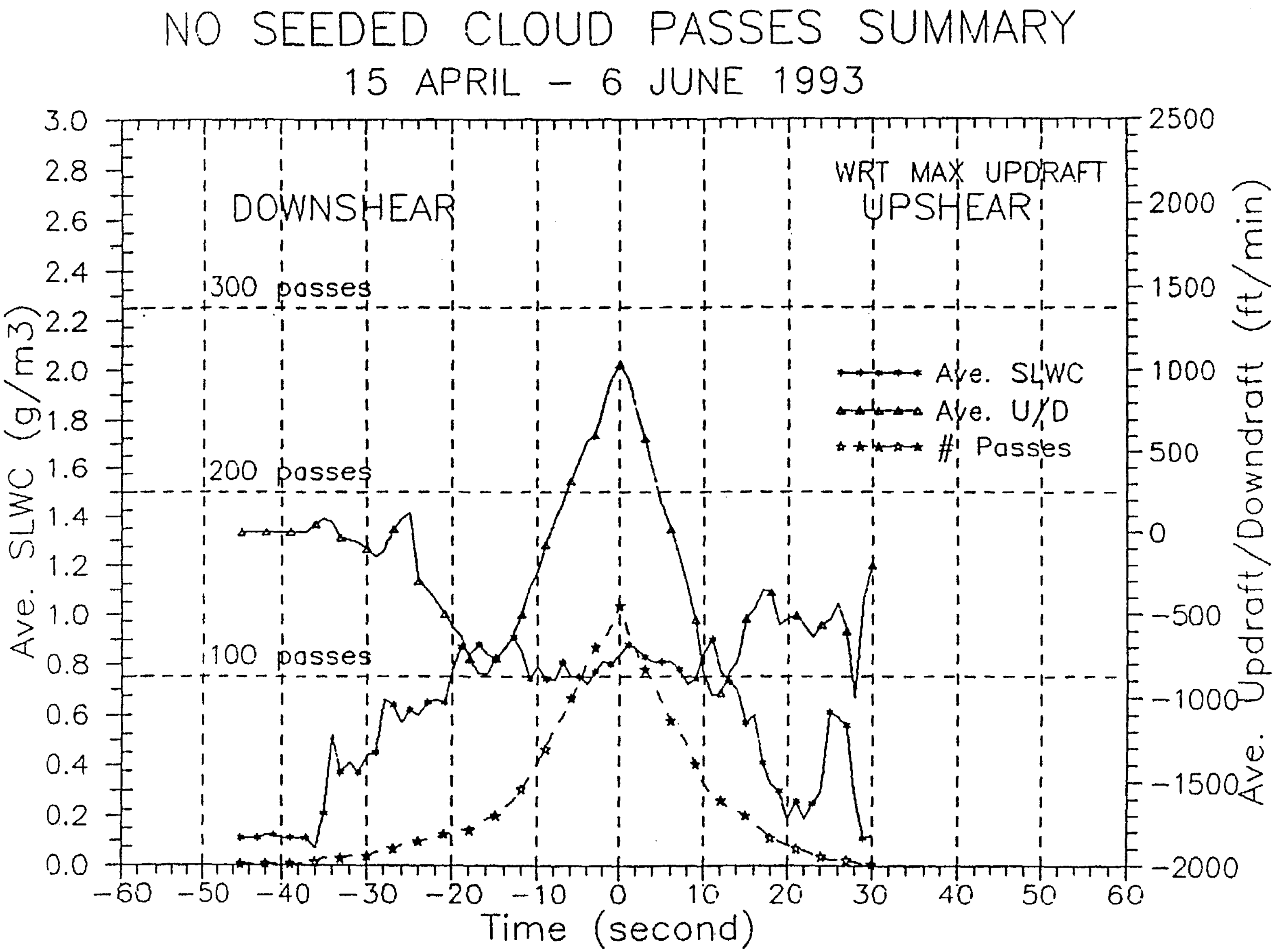

Figure B.II.4. - Plot of mean SLWC and updraft relative to the point in the cloud where the updraft reached the highest pass value for all cloud penetrations on days with NS units in 1993. The third line corresponds to the number of cloud passes as a function of time. The plot is divided into upshear and downshear directions.

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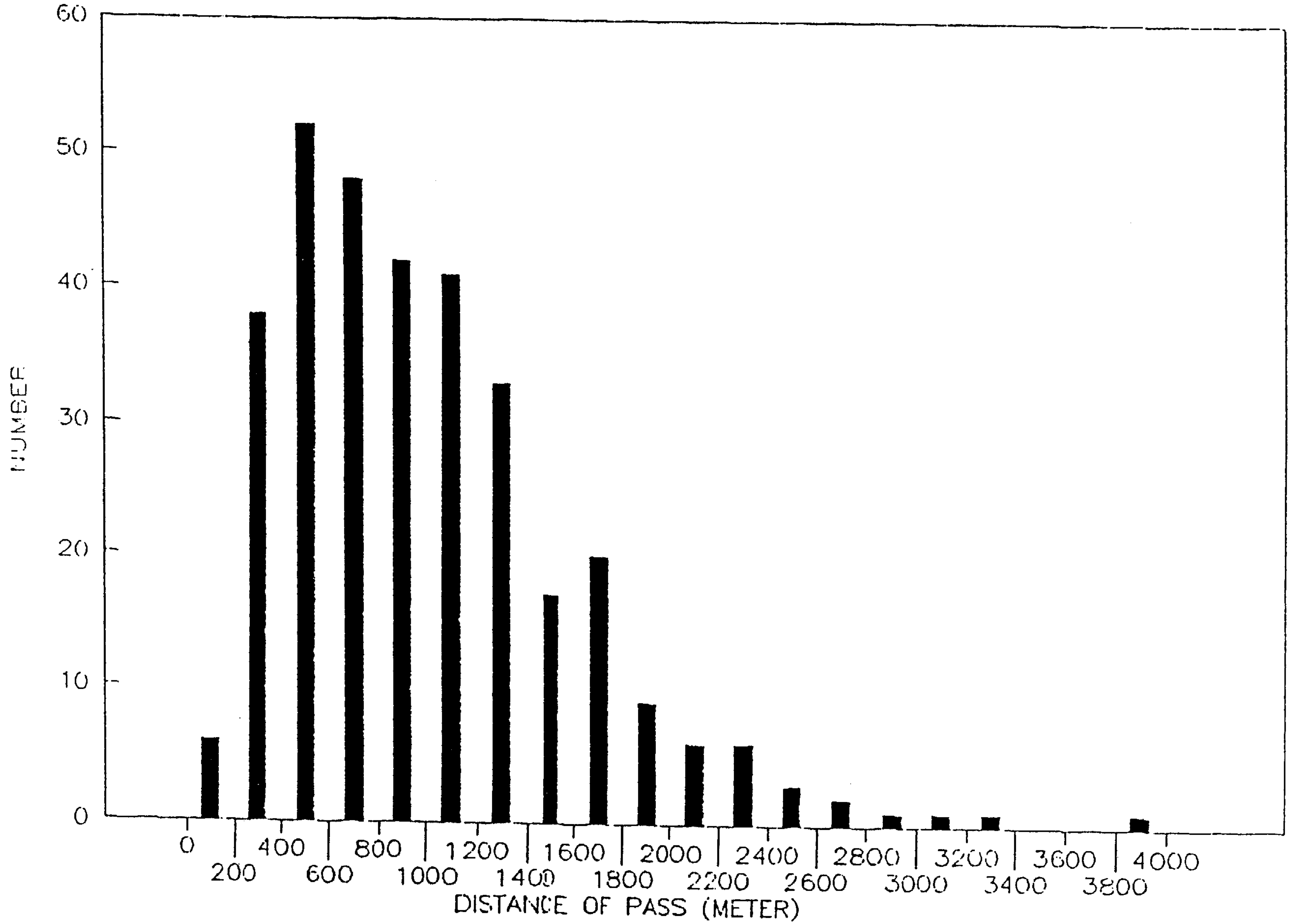

Figure B.II.5. - Frequency plot of half-pass distances as determined by aircraft penetration of clouds during the conduct of randomized cold cloud seeding experimentation in 1993. The pass distances have been divided by two to approximate cloud radius.

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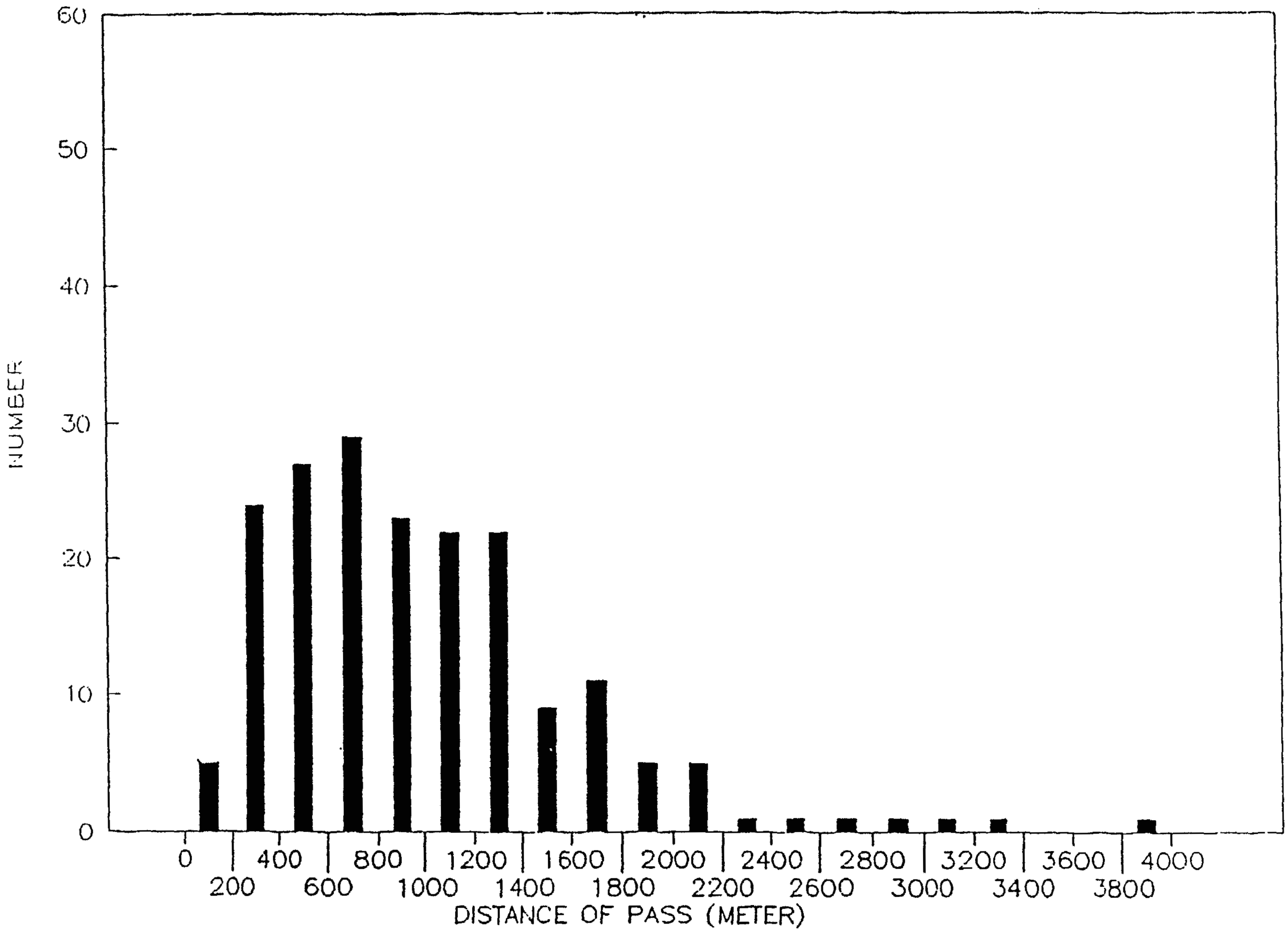

Figure B.II.6. - Frequency plot of half-pass distances as determined by aircraft penetration of clouds during the conduct of randomized cold cloud seeding experimentation in 1993 on days with experimental units receiving AgI seeding. The pass distances have been divided by two to approximate cloud radius.

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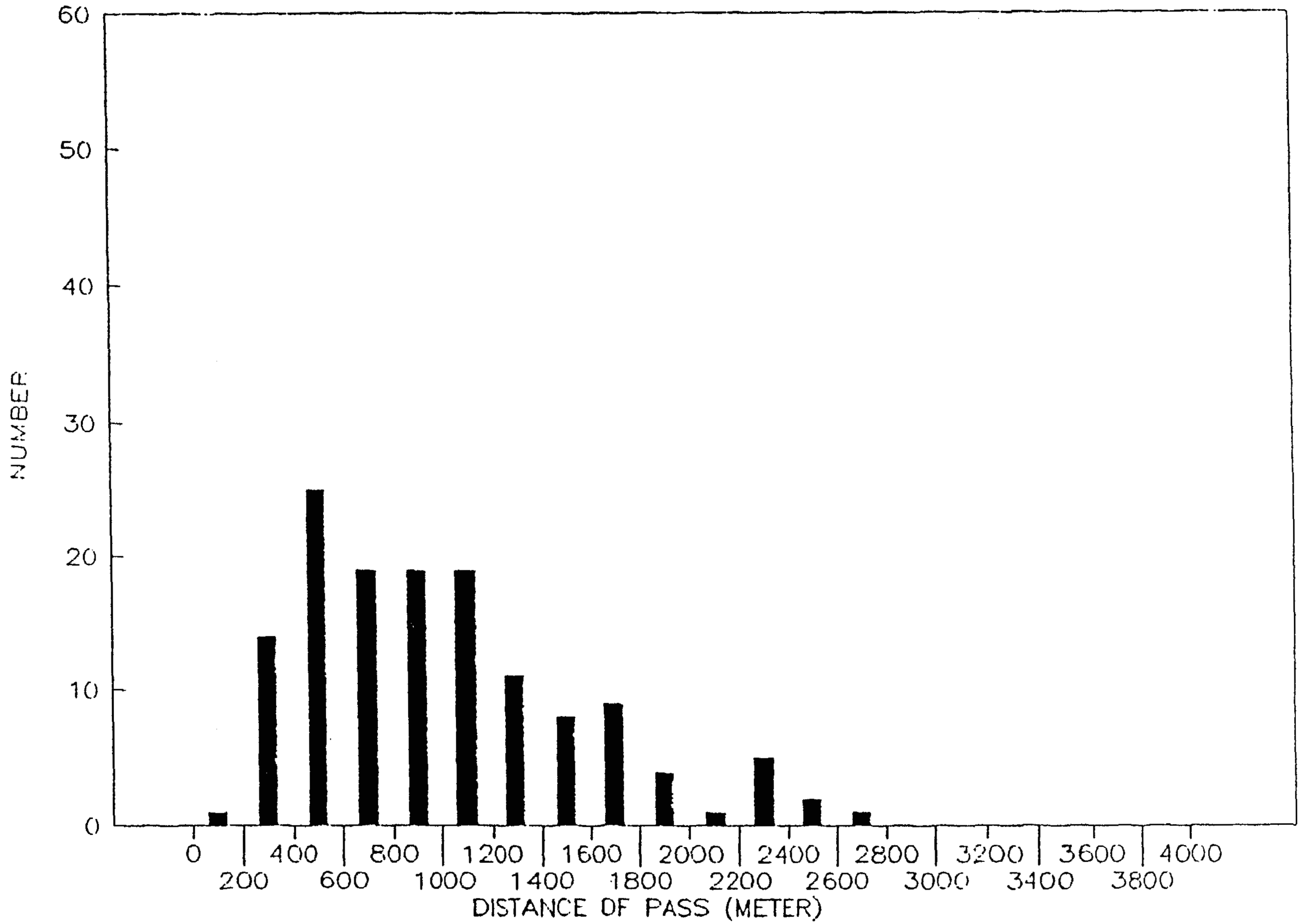

Figure B.II.7. - Frequency plot of cloud-pass distances as determined by aircraft penetration of cloud during the conduct of randomized cold cloud seeding experimentation in 1993 on days with experimental units receiving simulated AgI treatment. The pass distances have been divided by two to approximate cloud radius.

B.II.3 Analysis of the Radar Data

The three-dimensional structures of the convective rain cells were monitored and recorded by the Enterprise S-band radar, which was located at Omkoi (see part I for specifications). The radar scanned the whole volume of the troposphere in the target area every 5 minutes. The recorded radar data are the primary source of information for the scientific evaluation of the effect of seeding.

The three-dimensional matrices of the radar reflectivity factor, which were used in the next steps to specify the history of the three-dimensional structures of the cells, were saved in 5-minute time intervals. The data were already recorded by the SIGMET radar processor in dBZ units.

The initial focus of this study is on individual convective cells within clouds and cloud systems rather than on multi-cell echoes because the cell is the fundamental building block of all convective weather systems. As in earlier work (Gagin et. al., 1985 and 1986; Rosenfeld, 1987; Rosenfeld and Woodley, 1989; 1993), convective cells are defined as entities with at least three closed radar reflectivity isolines spaced at 1-dBZ intervals at the cloud-base level. All the radar echoes greater than 12 dBZ are partitioned between these entities; the division lines coincide with the trough lines on the reflectivity map.

Rosenfeld (1987) developed a special method for the study of cells that compose convective rain systems. This method consists of a package of computer programs that use pattern recognition techniques on three-dimensional digital radar data to identify the rain cells, track them with time and calculate their properties. The product of the computations is a comprehensive data base of physically meaningful properties of rain cells, which can be used to infer the internal structure and the dynamics of convective rain systems. This data base includes the production of time-height reflectivity cross-sections of the tracked cells, which are very useful to obtain a physical understanding of the precipitation evolution in the clouds.

The cell tracking programs produce a data base of the tracked cells. Their data base consists of tables of cell properties during their lifetimes. There are 90 INSTANTANEOUS values for each scan at which the cell was scanned by the radar (usually 5 minutes apart). Each cell also has LIFE CYCLE values, which contain cumulative cell properties or the life cycle maximum of the instantaneous properties.

The cell data can be analyzed with both the "short track" and "long track" approaches. The "short track" approach follows the cells until they either dissipate or merge with neighboring cells at a particular reflectivity contour. The "long track" is an objective approach that allows for cell tracking after merger. "Long track" appears to be superior to "short track" because it permits a more complete history of each cell (Rosenfeld and Woodley, 1989). This "long track" analysis is emphasized in this paper.

A total of 151 cells were treated (AgI or simulated AgI) in 1991 and 1993, and were subsequently tracked in the long-track analyses. These cells are the input data for the ensemble cell analyses that follow. All rainfalls were calculated from the Z (Reflectivity)-R (Rainfall Rate) relationship: $Z = 300R^{1.4}$, which was used by Woodley (1970) for radar estimation of rain from convective clouds over south Florida.

No analysis was possible for April 18, 1993, on which AgI seeding was done. The radar was not operated properly on this day, resulting in the loss of the data necessary to track the cells and calculate their properties. Thus, 14 experimental units (7 S and 7 NS) are available for the inference of treatment effects. These effects are discussed in the next section.

B.II.4 Search for Effects of Cold Cloud Seeding

B.II.4.2 Statistical significance tests

The probability that the AARRP cell results are caused by chance was calculated by a refinement of the Monte Carlo rerandomization test (Gabriel and Feder, 1969). This calculation was done in the following steps:

1. A randomization reallocation of the experimental random cases to S and NS was made. All the treated cells in an experimental random case were assigned the same treatment which was drawn for the case.

2. The *SR* between all the S and NS cells, pulled together from all the S and NS randomized cases, was calculated.

3. Steps 1 and 2 were repeated for 3000 permutations, and a sorted vector of the *SR*'s, obtained in the permutations, was produced.

4. The fraction (*P*, in percent) of the randomly obtained *SR*'s, which are larger than the observed one in the real experimental allocation, is the chance that the experimental result is caused by the natural variability. This chance is referred to as the "significance level."

B.II.4.3 Results of the cell analyses

The mean cell properties for the Thailand data set are provided in table B.II.1. NS refers to cells that were not seeded and S to cells that received AgI treatment. NCLMAX is the mean maximum number of cells within each cell cluster. S/NS is the single ratio of S to NS cell properties and the significance of each observed *SR* was calculated using rerandomization procedures.

Examination of the presentation in table B.II.1 suggests that the S cells produced more rainfall than the NS cells by virtue of covering more area and having greater durations and larger rain volume rates. This result, although physically plausible and in agreement with the results in Texas (Rosenfeld and Woodley, 1989; 1993), could well be caused by chance because of the small sample. No single result can be seen to have a significance value anywhere near 5 percent.

The next step was to examine only those cases having warm cloud bases, when coalescence would be more active and rainwater would be present in vigorous updrafts above the freezing level. Table B.I.1 in part I shows that several of the cases had rather cold cloud bases.

These cool cloud bases might strike the uninitiated scientist as odd, considering the tropical location of the experimentation. As discussed by Woodley et al. (1993), however, high, cool cloud bases are fairly typical of Thailand during the pre-monsoon period, when conditions are relatively dry. During the monsoon itself, cloud bases are lower and warmer. Woodley and Rosenfeld (1993) estimate that the onset of the monsoon at Chiang Mai in 1993 took place on May 19. Both random units obtained after this date have base temperatures > 20 °C.

Table B.II.1. - Means, single ratios, and the rerandomization significance levels of the ratios for the various cell properties for the 14 experimental units obtained in Thailand through 1993. The data are for the long-tracked cells.

Variable	No. of Cells S	No. of Cells NS	S	NS	S/NS	Rerand. Sig. (%)
R_{vol} (10^3 m^3)	87	64	190.6	113.1	1.69	38.4
H_{max} (km)	87	64	9.6	9.8	0.98	59.6
Z_{max} (dBZ)	87	64	43.1	42.7	1.01	47.0
A_{max} (km^2)	87	64	69.6	55.8	1.25	21.0
DUR (min)	87	64	43.1	37.8	1.14	30.8
RVR_{max} (10^3 m^3/h)	87	64	413.8	290.5	1.42	33.1
NCLMAX	87	64	19.5	11.9	1.64	27.5
MERGERS	87	64	1.9	1.7	1.07	40.5

The Thai cell results for those 10 cases in which the cloud base temperature was > 16 °C are provided in table B.II.2. The 16 °C cutoff is purely arbitrary, but, in examining the data in table B.I.1 of part I, this cutoff seemed as logical as any other. Note that the ratio of S to NS has increased for every listed parameter except for the number of cell mergers, which stayed the same. The apparent effect on cell rainfall has increased to 2.25, which is comparable to what has been observed in Texas (Rosenfeld and Woodley, 1993). All significance values have improved as well, but they are still far short of what is needed for high confidence in ascribing the results to AgI seeding.

Table B.II.2.- Means, single ratios, and the rerandomization significance levels of the ratios for the various cell properties for the 10 experimental units obtained in Thailand whose cloud base temperatures were > 16 °C. The data are for the long-tracked cells.

Variable	No. of Cells S	No. of Cells NS	S	NS	S/NS	Rerand. Sig. (%)
R_{vol} (10^3 m^3)	61	47	261.1	115.9	2.25	30.0
H_{max} (km)	61	47	10.0	9.4	1.06	34.1
Z_{max} (dBZ)	61	47	46.4	42.2	1.10	16.2
A_{max} (km^2)	61	47	82.4	48.1	1.71	3.2
DUR (min)	61	47	52.4	39.4	1.33	11.9
RVR_{max} (10^3 m^3/h)	61	47	535.4	256.4	2.09	19.8
NCLMAX	61	47	24.9	13.7	1.78	23.6
MERGERS	61	47	1.9	1.7	1.07	38.0

It is interesting to note from the presentations in tables B.II.1 and B.II.2 that the apparent 100-percent increases in mean cell rainfall have taken place without an appreciable increase in mean cell heights. This increase was also the case in Texas, where the increase in mean cell height was < 10 percent. In Florida, on the other hand, the mean increase in cell height

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was about 20 percent. A potential explanation for these results, involving the expenditure of the seeding-induced buoyancy to sustain the increased water mass and leaving little left over for increased vertical growth of the cloud, has been addressed by the conceptual model that was discussed in part I.

At this point, however, one cannot discount another possible explanation. If AgI seeding makes cloud top less reflective because of the interception of much of the water mass by graupel lower in the cloud leaving small ice crystals near cloud top, the height differences might be explained by differences in the radars that were used to make the echo height observations. Five-centimeter (C-band) radars were used to make the echo height observations in Florida (Gagin et al., 1986) and in Texas (Rosenfeld and Woodley, 1989). In Thailand, however, a 10-centimeter (S-band) radar, which is less sensitive to small ice hydrometeors than the 5-centimeter radar, was used to make the echo top observations. Therefore, the echo tops of the S cells in Thailand may have been underestimated relative to the NS cells because the cloud tops may have been made less reflective at their tops by seeding.

These Thai results were the impetus for re-examining the Texas cell results (Rosenfeld and Woodley, 1993) as a function of cloud base temperature. Tables B.II.3 and B.II.4 provide the Texas results for those units whose base temperatures were ≤ 16 °C (table B.II.3) and > 16 °C (table B.II.4). Note that even in the cold base partition, the *SR* of S to NS rainfalls still is a factor of 2.08. Note also, however, that the *SR* of S to NS echo top heights is only 0.95. Thus, the cooler cloud base situation still has a 100-percent increase in cell rainfall, but increased vertical cloud growth is apparently not responsible for the rain increases.

In the warm base partition, the apparent effect of treatment is even larger at a factor of 2.85. The *SR* of echo top heights is 1.23, which is comparable to what has been observed in Florida. This observation suggests that in the warm base situation, when the concentration of rainwater at the level of treatment should be greater, the seeding-induced buoyancy is large enough both to sustain the increased water mass and to increase echo top height. In contrast, the *SR* of echo heights in Thailand is only 1.06 within the warm-base partition, but this result may be caused by the underestimation of the echo tops of the S cells by the S-band radar.

Further quantification of the seeding effect as a function of cloud-base temperature is provided on figure B.II.8, which shows plots of the ratio of mean S to NS values (the seeding effect ratio) versus cloud-base temperature for echo height and rain volume in Texas and in Thailand. The plots were constructed by including cases cumulatively, beginning with the case with the coldest cloud-base temperature (fig. B.II.8). The right edge of each plot, therefore, represents the S/NS ratio of cell height and rain volume for all cases. Note that the plots for both regions show increasing S/NS values for cell heights and rain volumes as cloud base temperature increases.

A curious feature of the presentation on figure B.II.8 is the 3 °C offset in the S/NS plots for cell rain volume in Thailand and Texas. Note that the cumulative plot is > 1.0 for cloud-base temperatures > 14 °C in Texas, whereas the plot for Thailand is not > 1.0 until a cloud base temperature of 17 °C is reached. The most likely explanation at this point is that this result is an artifact of the small sample.

Table B.II.3. - Means, single ratios, and the rerandomization significance levels of the ratios for the various cell properties for the 14 experimental units obtained in Texas, whose cloud base temperatures were ≤16 °C. The data are for the long-tracked cells.

Variable	No. of Cells		S	NS	S/NS	Rerand. Sig. (%)
	S	NS				
R_{vol} (10^3 m^3)	49	49	287.8	138.4	2.08	11.9
H_{max} (km)	49	49	9.5	10.1	0.95	60.5
Z_{max} (dBZ)	49	49	46.4	45.3	1.02	41.5
A_{max} (km^2)	49	49	99.1	64.1	1.55	12.7
DUR (min)	49	49	58.0	52.7	1.10	35.5
RVR_{max} (10^3 m^3/h)	49	49	564.4	386.3	1.46	18.4
NCLMAX	49	49	44.0	43.2	1.02	48.3
MERGERS	49	49	3.1	2.0	1.53	14.0

Table B.II.4.- Means, single ratios, and the rerandomization significance levels of the ratios for the various cell properties for the 10 experimental units obtained in Texas whose cloud base temperatures were > 16 °C. The data are for the long-tracked cells.

Variable	No. of Cells		S	NS	S/NS	Rerand. Sig. (%)
	S	NS				
R_{vol} (10^3 m^3)	44	41	206.2	72.3	2.85	11.0
H_{max} (km)	44	41	10.7	8.7	1.23	21.3
Z_{max} (dBZ)	44	41	45.2	45.2	1.00	49.5
A_{max} (km^2)	44	41	63.3	49.9	1.27	22.1
DUR (min)	44	41	62.3	33.8	1.85	3.03
RVR_{max} (10^3 m^3/h)	44	41	395.9	288.0	1.37	28.9
NCLMAX	44	41	52.5	51.6	1.02	48.2
MERGERS	44	41	3.2	1.2	2.76	4.8

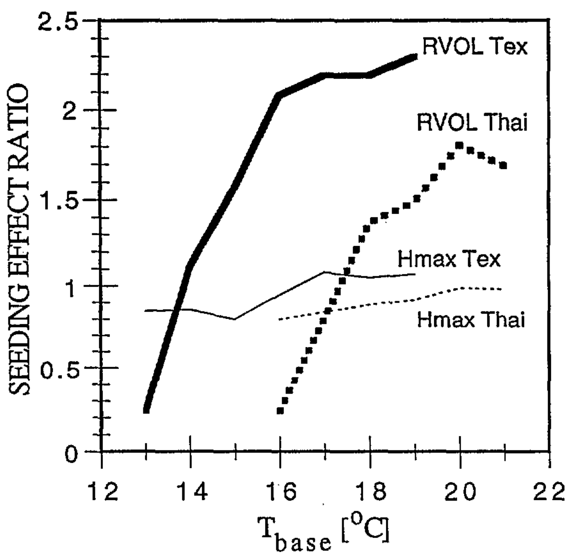

Figure B.II.8. - The indicated seeding effects on cell rain volume and maximum echo top height in Texas and Thailand as a function of cloud-base temperature. The cases are considered cumulatively, beginning at the coldest observed cloud-base temperature. The right terminus of each line provides the overall effect from all cases.

An alternative, intriguing, but highly speculative explanation for the plot differences is that, for a given cloud-base temperature, coalescence may be less active in Thailand than in Texas, such that warmer cloud base temperatures are necessary in Thailand for the production of raindrops. Because the glaciation of supercooled raindrops is the primary source of energy for dynamic seeding, this explanation would mean that warmer cloud base temperatures would be required in Thailand relative to Texas for the production of positive seeding effects.

Coalescence may, in fact, be less efficient in Thailand during the pre-monsoon period than it is in Texas in August, when most of the Texas experimentation has been conducted. In Thailand, prior to the monsoon, the lower atmosphere is typically quite polluted with smoke from the burning of organic trash. Extrapolating from the work of Warner and Twomey (1967), who showed that the burning of slash material from sugar cane produced very high concentrations of CCN (cloud condensation nuclei), it might be surmised that this occurrence is also the case in the polluted air of pre-monsoon Thailand. These nuclei would produce many small cloud droplets which would inhibit the coalescence process. In west Texas, on the other hand, no such pollution typically exists during dynamic seeding experimentation, and the natural CCN are operative. This uncertainty can only be resolved by a vigorous program of CCN measurement in both regions.

One of the more interesting Thai analyses is the presentation on figure B.II.9, which is a semi-log plot that shows the mean S and NS rainfalls by height interval. Note that in the interval between 7 and 11 kilometers, the S cells produce more rainfall than NS cells *of the same height*. This increase suggests a more efficient microphysical process in the S cells whereby more water mass is accumulated within its interior than exists within NS cells of the same height. This result is very similar to the results that were obtained in Texas (fig. 4 in Rosenfeld and Woodley; 1993).

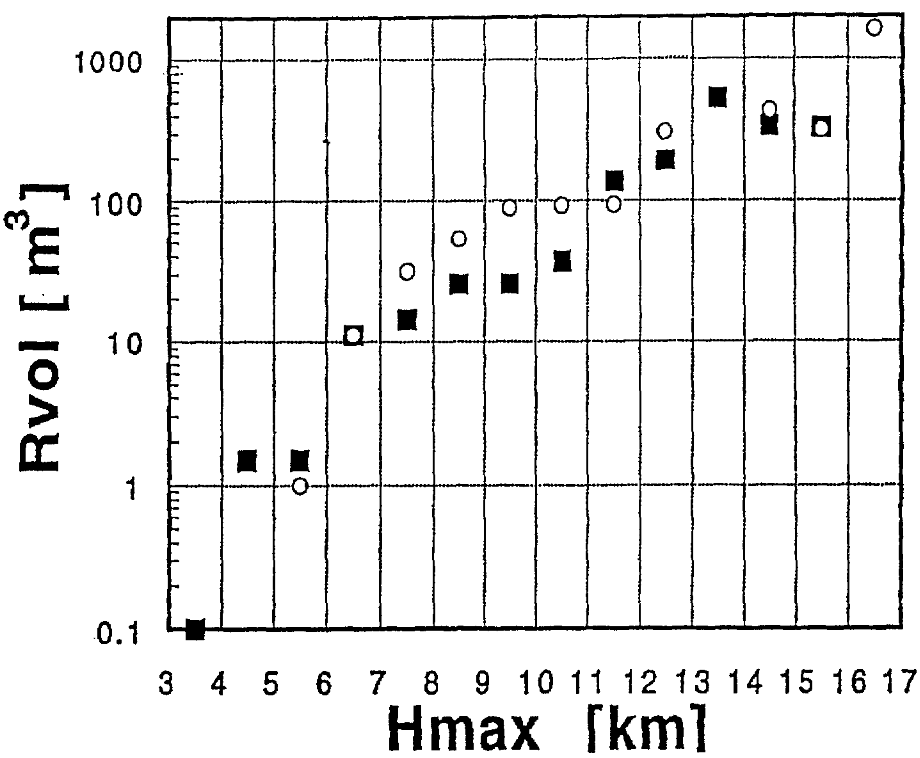

Figure B.II.9. - Semi-log plots of mean S and mean NS cell rain volumes within 1-kilometer height intervals. The open circles represent S data and the solid squares represent NS data.

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Plots of the mean properties of the S and NS cells as a function of time for all cells and for those cells in units with base temperatures > 16 °C are provided on figures B.II.10 and B.II.11, respectively. The means are for those cells that existed at each time interval.

Examination of the plots for all cells (fig. B.II.10) shows greater echo areas and rainfalls for the S cells both before and after the initial treatment. The S and NS reflectivity plots are little different, although the S and NS height plots suggest slightly taller NS cells. By 1 hour after initial treatment, all differences favor the NS cells, although less than one-third of the cells remain in the sample at this time.

Examination of the plots for all cells with warm bases (fig. B.II.11), shows essentially the same picture, although the S and NS differences before and after treatment are larger. Again, the few NS cells remaining in the sample by 1 hour after initial treatment are stronger than the S cells. This result is different from the Texas results that showed the S versus NS differences increasing with time (Rosenfeld and Woodley, 1993).

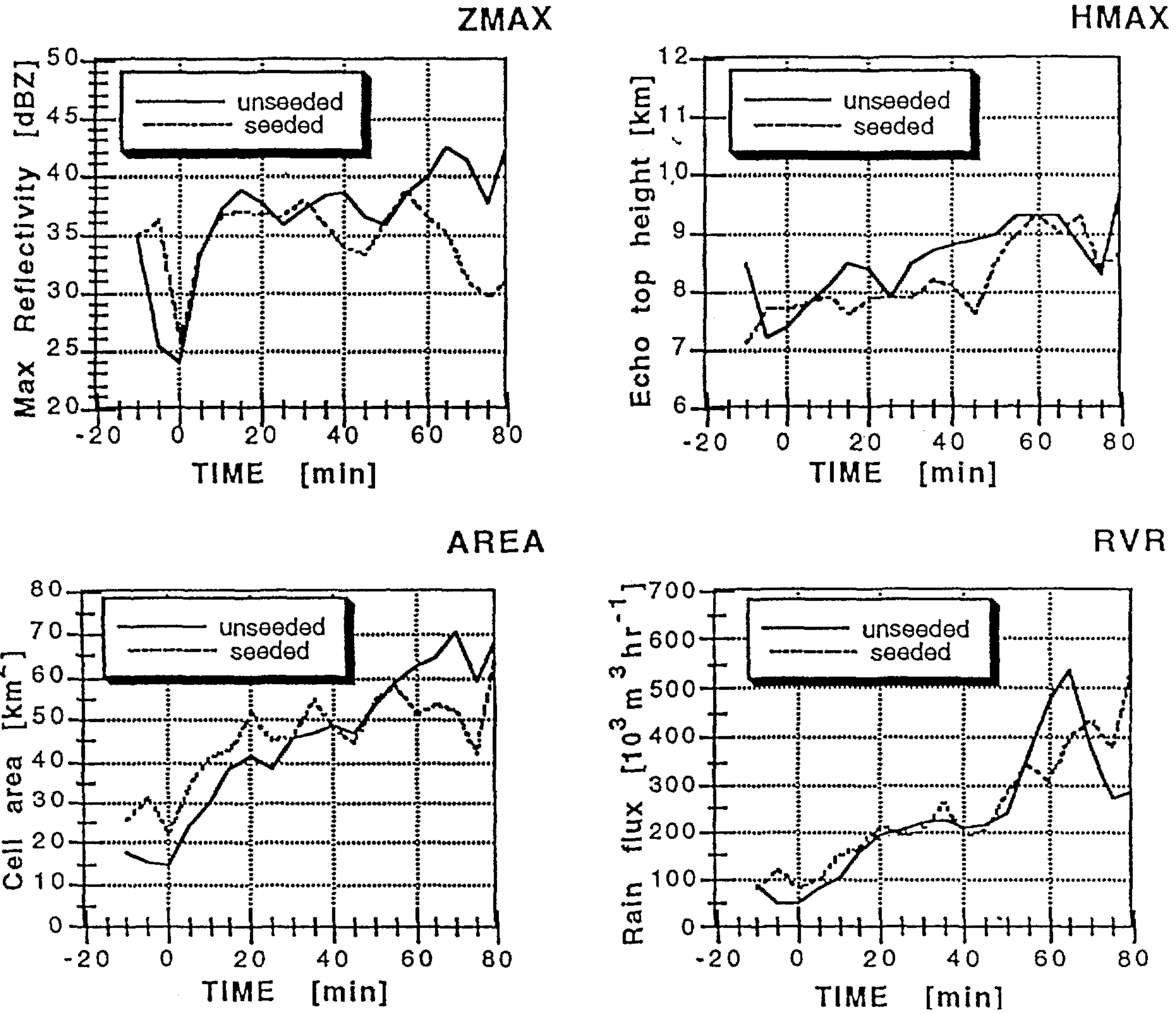

Figure B.II.10. - Line plots of mean S and mean NS reflectivities (upper left), cell heights (upper right), areas (lower left), and rain volume rates (lower right) for all of the cell data. The means have been calculated at each interval based on the number of cells in the sample at that time.

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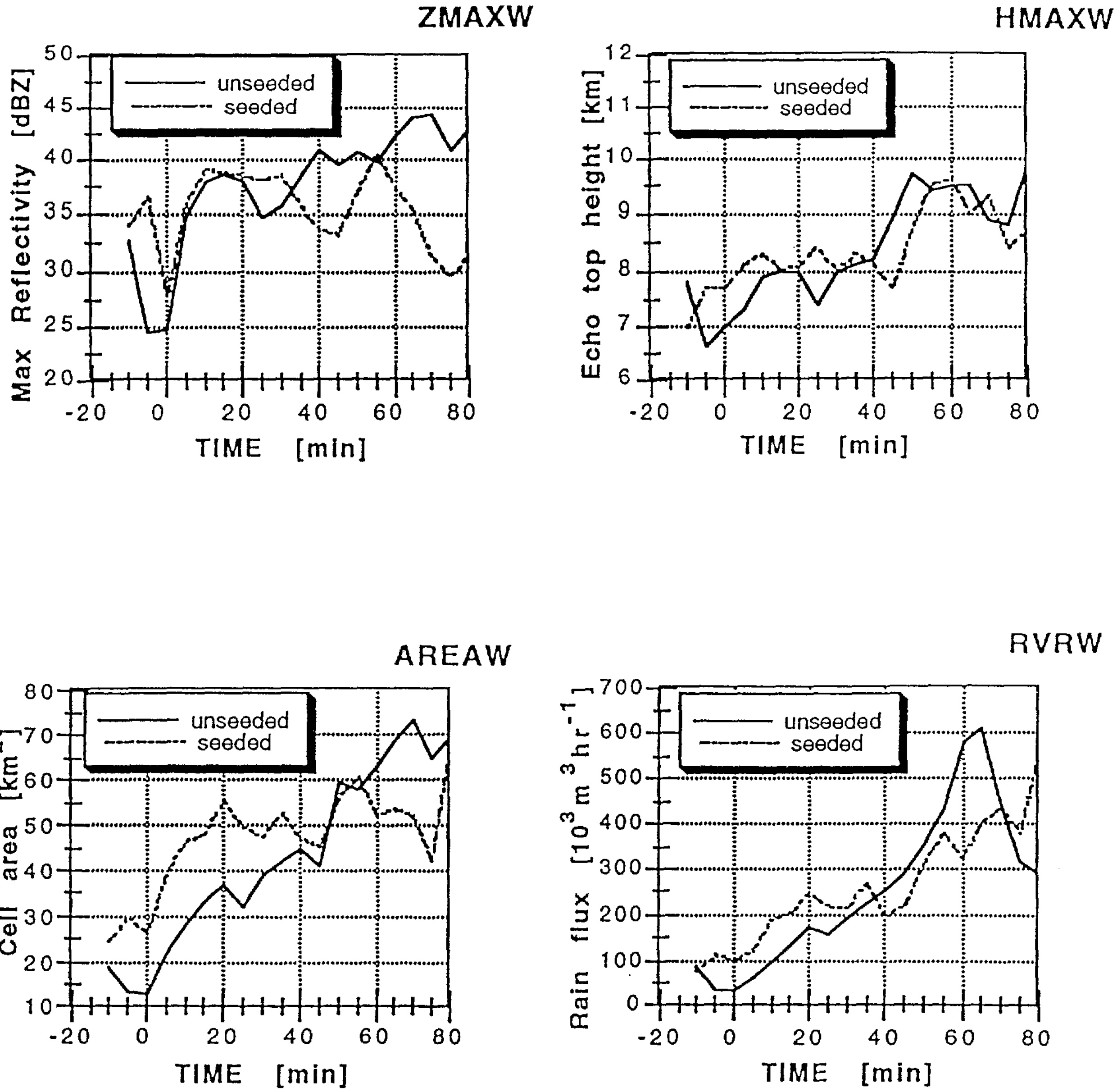

Figure B.II.11. - As in figure B.II.10, but for the cell data when cloud-base temperatures exceeded 16 °C.

A more representative picture of the effect of seeding on mean cell areas and rainfall flux is the calculation by time interval that includes the zero (0) values of those cells that had already dissipated. The plots for all cells are provided on figure B.II.12 and for only those cells with warm bases on figure B.II.13.

The all cells plots (fig. B.II.12) show smaller pre-treatment and post-treatment differences; the S cell areas and rain fluxes generally exceed the NS values until 60 minutes after initial treatment. The plots for only the warm-based cells (fig. B.II.13) show essentially the same picture as on figure B.II.12, although the S-NS differences are substantially greater.

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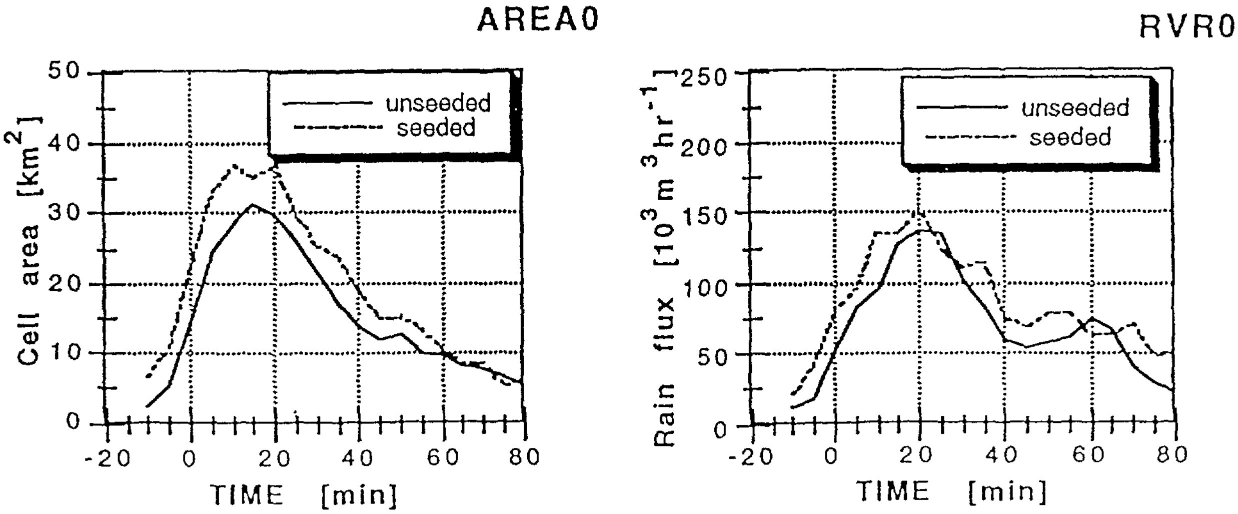

Figure B.II.12. - Line plots of mean S and mean NS cell areas (*A*) (at top) and rain and rain volume rates (*R*) (at bottom) for all of the cell data. The mean *A* and *R* values for each time interval were calculated by inputting zero values for those cells that had dissipated previously.

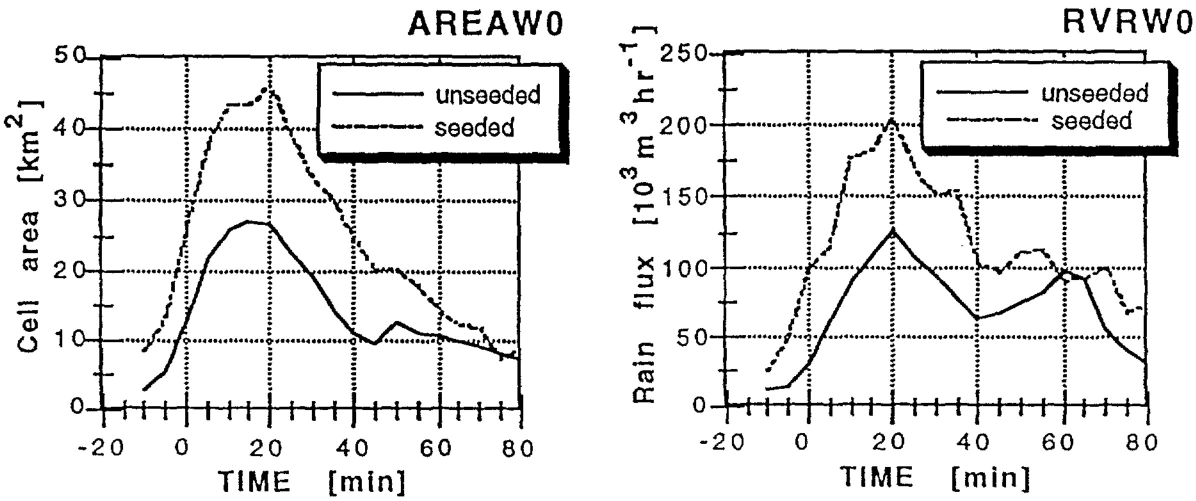

Figure B.II.13. - As in Figure B.II.12, but for the cell data when cloud-base temperatures exceeded 16 °C.

Many readers might feel intuitively that the higher mean rainfall for the S cells prior to treatment represents a bias favoring the S sample. This bias does not appear to be the case for this sample, as can be seen in the scatter plot for the NS and S cells of total pre-treatment cell rainfall versus the total rainfall produced by the cell in its lifetime (fig. B.II.14). The scatter is large in both plots. Note that all but one of the cells in both samples, producing > 10^6 cubic meters in rain volume had zero pre-treatment rainfalls. The one exception in the S sample had a modest pre-treatment rainfall, and its position in the plot could well be a function of the seeding intervention. Note further that all cells having pre-treatment rainfalls $\geq 40 \times 10^3$ cubic meters had very small lifetime rainfalls. If these cells are eliminated from both samples, the new ratio of mean S to NS post-treatment cell rainfalls is 1.77 versus the original value of 1.69. Therefore, a large pre-treatment rainfall appears to be a liability to a cell's post-treatment rainfall.

Further physical insight into the cell results was provided by the construction of time-height reflectivity cross sections for the entire cell data set, as shown on figure B.II.15, and for the cells having base temperatures > 16 °C on figure B.II.16. The numbers above the abscissa indicate the number of cells contributing to the composite versus time. The S cross-section for all the cell data (top) appears to be more stratified than the NS cross-section (bottom) beginning 30 minutes after initial seeding. The NS cells left in the sample at that time are also taller than the S cells that remain, in contrast with the results obtained in Texas.

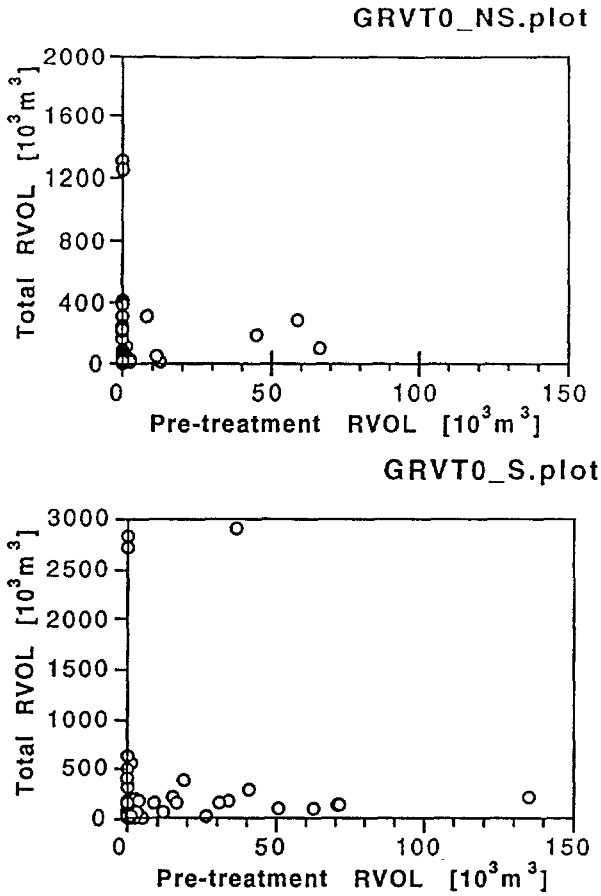

Figure B.II.14. - Scatter plot of the total rainfall produced by the NS (top) and S (bottom) cells (units: $m^3 \times 10^3$) prior to real or simulated treatment versus the total rainfall produced by the cells in their lifetimes.

The results for the warm-based cells (fig. B.II.16) look similar to those of figure B.II.15. Only after subtracting the patterns for the warm cases (i.e., S time height profile minus NS time height profile) does something of interest appear (fig. B.II.17). Note that a positive reflectivity difference of up to 11 dBZ is centered between 6 and 8 kilometers at the time of initial treatment, which persists until about 30 minutes thereafter.

Such a difference pattern was observed also in Texas, although the differences were initially smaller in Texas than in Thailand (fig. 3c in Rosenfeld and Woodley, 1993). Such positive reflectivity differences are consistent with the formation of graupel particles following AgI seeding as postulated in the conceptual model. Beyond that, however, the difference patterns in Thailand and Texas are quite disparate. The S-NS reflectivity differences in Thailand become slightly negative (below 10 kilometers) with time, indicating that the few NS cells that remain in the sample are stronger than the few S cells that persist. In Texas, on the other hand, the differences become strongly more positive with time, indicating stronger S than NS cells long after the initial treatment.

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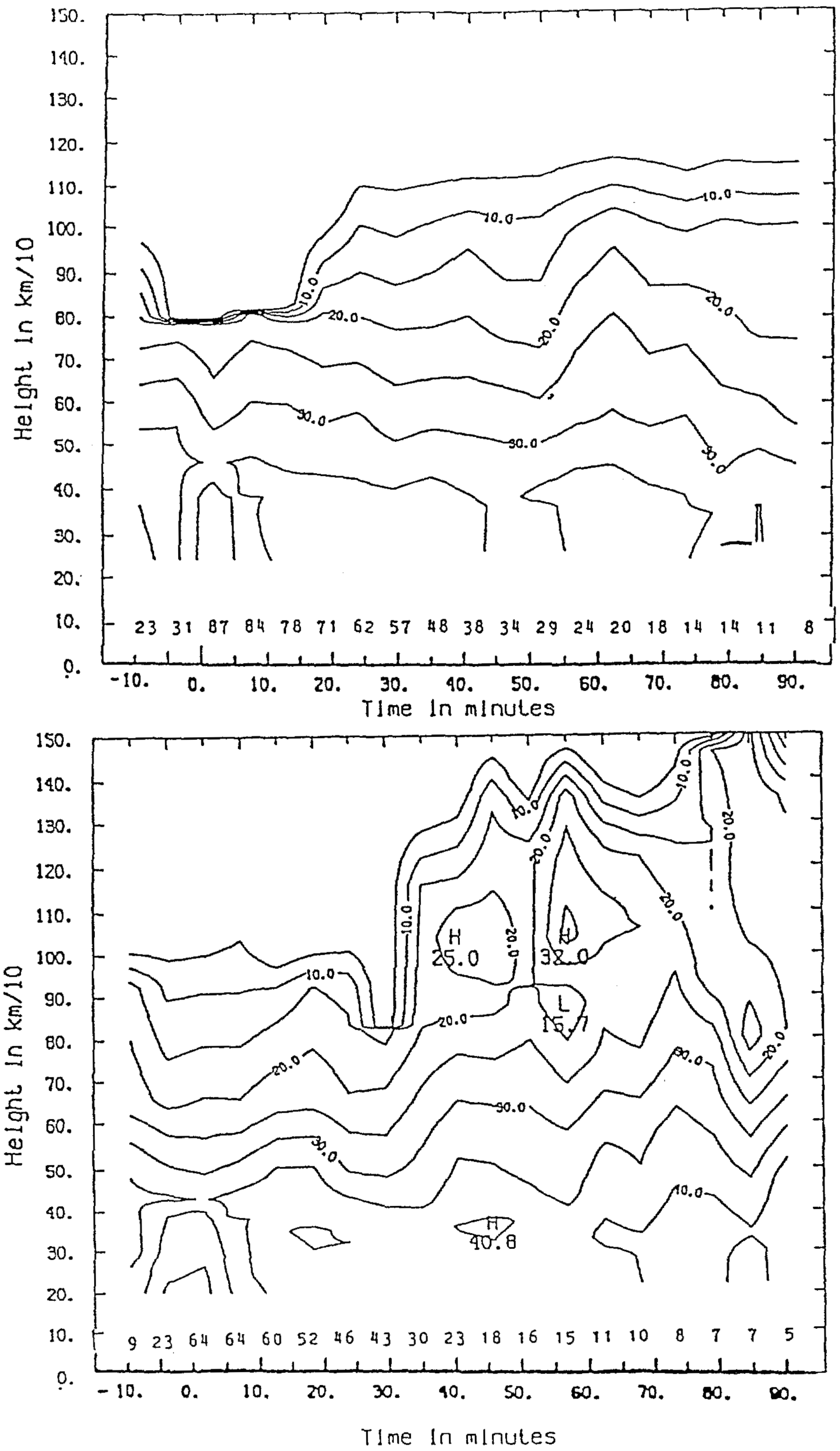

Figure B.II.15. - Composite time-height reflectivity (dBZ) plots of the cells treated with AgI (top) and for the cells that received simulated AgI treatment (bottom). The numbers above the abscissa refer to the number of cells (NC) in the sample at that time interval. The "0" time refers to the time of real or simulated treatment.

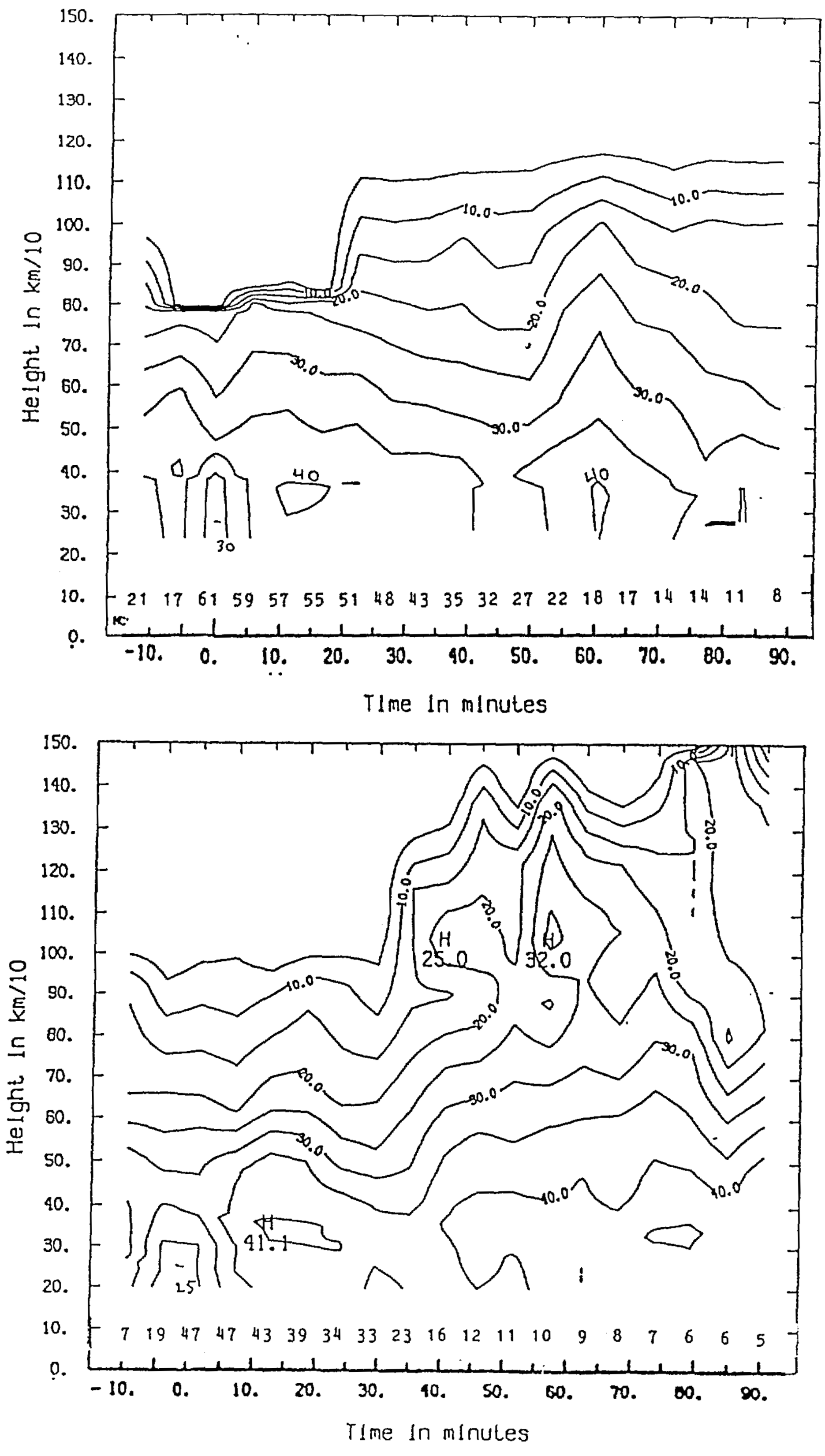

Figure B.II.16. - As in figure B.II.15, but for cells having cloud-base temperatures > 16 °C.

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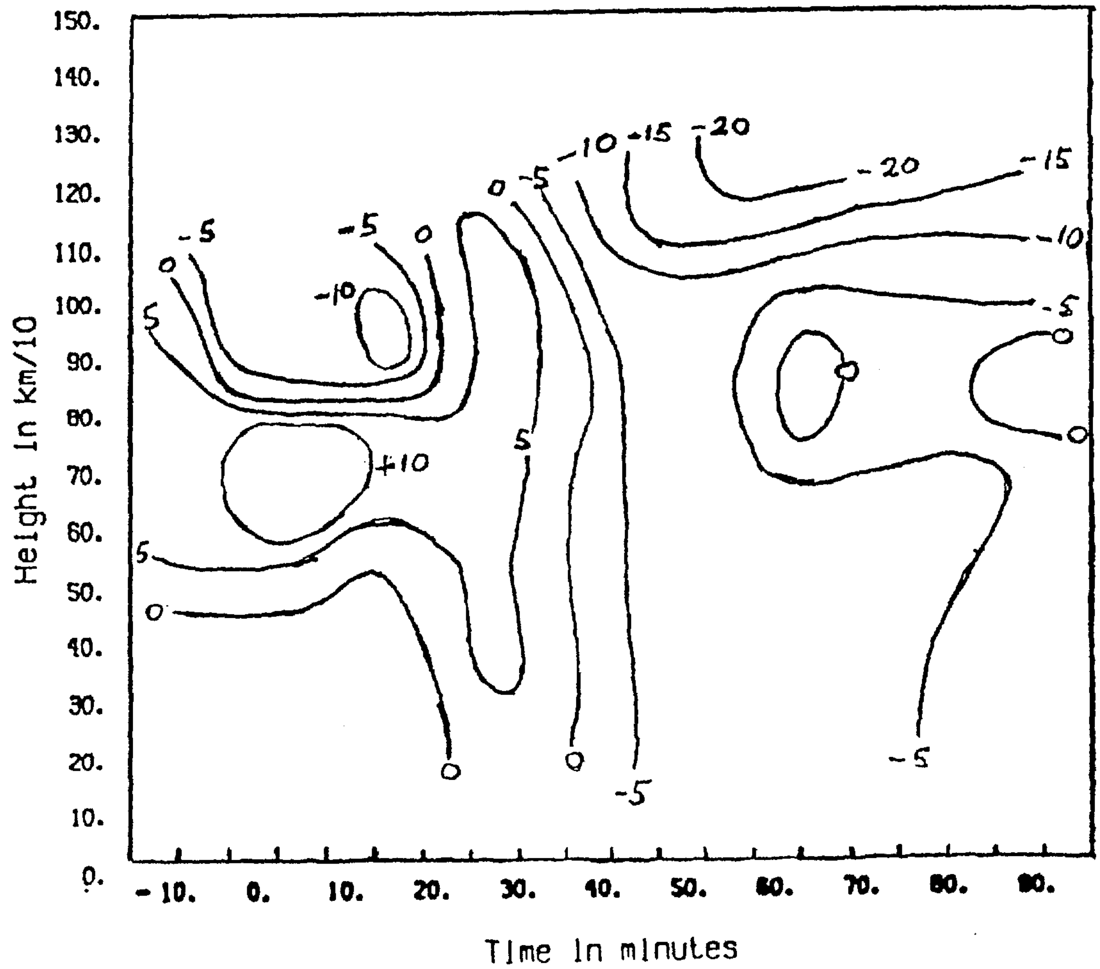

Figure B.II.17. - Difference (i.e., S-NS) composite time-height reflectivity (dBZ) plots for the cells having cloud-base temperatures > 16 °C. The "0" time marks the time of initial treatment (AgI or simulated AgI) (Units are dBZ).

B.II.4.4 Results for the experimental units

The last step in the analysis progression was an investigation of the effect of treatment on the experimental units themselves. Fourteen (7 S and 7 NS) experimental units were available for analysis. A listing of the input data by case, presented cumulatively in 30-minute intervals relative to the time of initial treatment, is provided in table B.II.5.

Examination of table B.II.5 reveals enormous case-to-case variability in the recorded values. In one example, the NS unit obtained on April 23, 1993, has a 2-hour cumulative rain volume that exceeds the cumulative rain volume from the NS unit obtained on May 4, 1993, by a factor of 194 in the same time period. This frightening result illustrates the difficulties that will be encountered in attempting to infer an effect of seeding on the experimental units with a limited sample. It is imperative, therefore, that the sample be increased and that predictors be found that can account for some of the natural rainfall variability that is inherent in the Thai experiments.

Table B.II.5.- Cumulative rainfall from the experimental units in time intervals relative to the time of initial treatment (units: $m^3 \times 10^3$).

SEED CASES

Date	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
08/07/91	829.3	518.8	879.3	1723.9	2077.1	2302.0	2595.0	3712.1	5452.0	7548.0	9673.3	11312.0
04/21/93	18.6	5.0	3.9	25.8	48.4	69.0	69.4	74.7	782.5	2200.7	3208.2	3761.5
04/22/93	44.9	42.2	238.1	916.2	1625.3	2338.0	4248.7	6321.5	6730.9	6763.1	6769.1	
04/25/93	18.6	16.3	48.3	189.3	533.4	991.7	1092.2					
05/07/93	0.1	0.1	33.8	250.3	700.5	2301.3	6001.8	7872.1	8225.9	8330.0	8375.8	
05/09/93	170.3	139.1	233.3	890.8	1556.9	1630.6	1644.4	1792.0	2197.3	2197.5		
05/27/93	351.1	196.5	265.0	519.3	656.1	763.1	888.5	979.7	987.2			

NO SEED CASES

Date	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
04/15/93	161.1	132.9	145.9	380.2	488.7	494.3						
04/20/93	1.4	1.2	19.6	559.1	985.1	1102.5						
04/23/93	27.3	27.3	518.9	1894.9	3469.3	4635.5	5139.6	5904.4	6957.5	7081.4		
04/29/93	343.1	248.7	292.9	636.2	1048.5	1380.7	1535.4	1541.9				
05/04/93	88.8	45.7	19.1	23.7	23.8	23.9						
05/08/93	0.1	0.1	151.8	429.7	755.6	883.8	887.9					
06/04/93	20.9	16.9	34.7	136.1	315.9	543.5	757.5	854.8	890.1	1020.2	1310.2	1487.5

The mean cumulative rainfalls by time period for the S and NS samples and the ratios of the former to the latter are provided in table B.II.6. The table contains two listings. The first provides the mean S and NS rainfalls and the ratios of the former to the latter. The second provides the same information, but with the wettest day in each sample deleted. This omission is done to see how sensitive the results are to outliers. No significance testing of the ratios has been done because such an exercise would have little meaning at this point in the Thai experiments. The sample is still much too small.

In examining the data presented in tables B.II.5 and B.II.6, a reader's first impression is that a bias favored the S units because the mean S rainfalls exceed the mean NS rainfalls by about a factor of 2 in the hour *prior* to initial treatment. This impression may not be correct for two reasons. First, the S mean is dominated by one case (i.e., August 7, 1991). Second, and more importantly, no correlation appears to exist between the pre-treatment rainfalls and the rainfalls that are produced by the experimental units subsequently. This lack of correlation can be seen in the log-log plot for the NS cases of the rainfall in the hour before initial treatment versus the rainfall in the 2 hours after initial treatment (fig. B.II.18). (The S units were not used in this exercise because AgI treatment is postulated to have altered the natural rainfalls.) The scatter is great and this limited sample provides no evidence that the pre-treatment unit rainfalls are a predictor of the rainfall that will be produced subsequently within the unit. If anything, the limited sample suggests a negative correlation (i.e., more rainfall prior to treatment means less rainfall afterwards). This result is virtually the same that was obtained for individual cells (fig. B.II.14).

The presentation in table B.II.6 and the plot of the S to NS ratios on figure B.II.19 show that the sample is quite sensitive to the deletion of the wettest unit from the S and NS samples. First, note that the apparent pre-treatment bias in the S sample totally disappears after deleting the wet case on August 7, 1991. Second, notice that the ratio of S to NS mean rainfalls increases continuously after the initial treatment when the wettest S and the wettest NS units are deleted.

The reader is urged to be cautious with the interpretation and dissemination of these results. Although they do provide the impetus to continue with the Thai experiments, no unequivocal argument that AgI treatment produces large increases in rainfall within the experimental units is justified at this time. With patience and a lot of hard work to increase the sample, such an argument might have some basis in the future.

B.II.5 Summary and Conclusions

Considering the time that the program has been in existence, tremendous progress has been made with the AARRP effort. It has been both an operational and scientific success to date. A state-of-the-art weather radar has been installed in a remote section of Thailand, and has provided the observations that are crucial to the assessment of cold cloud seeding effects. The AeroCommander aircraft and its flight crew of pilots and scientists have functioned well in assessing cloud conditions and in treating the clouds, using a seeding system that has operated flawlessly. The Thai scientists and their foreign advisors are melding together into a productive, collaborative research team.

Table B.II.6.- Mean cumulative rainfalls for the experimental units relative to the time of initial treatment (Units: $m^3 \times 10^3$).

All Data

	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
S	204.7	131.1	243.1	645.1	1028.2	1485.1	2362.8	3120.6	3638.3	4159.8	4586.2	4927.9
NS	91.8	67.5	169.0	580.0	1012.4	1294.8	1420.2	1544.2	1730.5	1736.0	1777.4	1802.8
S/NS	2.23	1.94	1.44	1.11	1.02	1.15	1.66	2.02	2.10	2.40	2.58	2.73
Data with Wettest Unit for the S and NS Samples Deleted												
S	100.6	66.5	137.1	465.3	853.4	1349.0	2324.1	3022.0	3336.0	3595.1	3771.7	3863.9
NS	102.6	74.2	110.7	360.9	602.9	738.0	800.3	817.5	859.3	845.1	893.4	923.0
S/NS	0.98	0.90	1.24	1.29	1.42	1.83	2.90	3.70	3.88	4.25	4.22	4.19

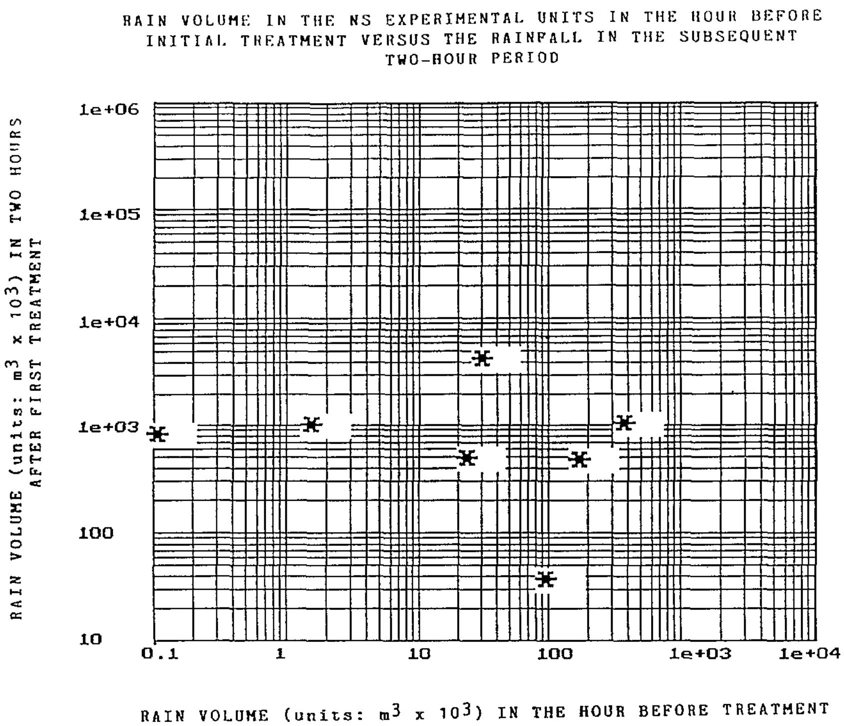

Figure B.II.18. - Log-log plot of the rain volume for the NS experimental units in the hour prior to initial simulated treatment versus the unit rain volume in the two subsequent hours.

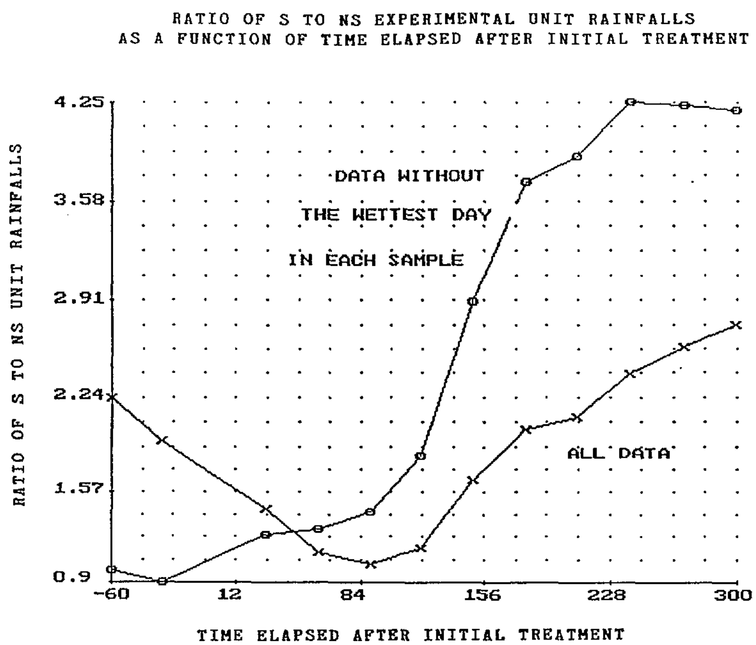

Figure B.II.19. - Plot of ratios of S to NS unit rain volumes by 30-minute time intervals relative to the time of initial treatment. The solid line is for all data. The dashed line plot is for the ratios that were calculated after the wettest day in the S and NS samples had been deleted.

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Scientific progress with the Thai cold cloud seeding effort has been substantial as well. It is now known that Thailand presents a rich harvest of supercooled clouds that are suitable for seeding intervention for the enhancement of their rainfalls. Thai pre-monsoon clouds are different from those that exist typically during the monsoon over the region of study. Cloud-base temperature is the major determinant of cloud conditions. When bases are high and cool, as is often the case in the pre-monsoon period, much of the water within the cloud apparently is concentrated in small cloud drops. Seeding of these clouds appears to result in rather slow glaciation and a rather weak vertical growth response of the cells. This result is in agreement with the predictions of Lamb et al. (1981) that glaciation in clouds with small supercooled drops will proceed rather slowly. When the bases are low and warm, as is the usual case during the monsoon, a substantial amount of the water that is encountered within the cloud at temperatures of about -8 °C is apparently in raindrops. Seeding of these clouds appears to cause rapid glaciation and explosive vertical growth in some circumstances. Although rainfall increases may be produced in both cloud types, the largest increases are likely produced in the clouds with warm cloud bases. This result is consistent with the conceptual model as presented and discussed in part I. Having such a model to guide the effort has been a major plus for the program.

The results of cold cloud seeding to date are consistent in most respects with the results that have been published previously for Florida and Texas (Gagin et al., 1986; Rosenfeld and Woodley, 1989; 1993). Initial results suggest that AgI seeding may have increased the cell rainfalls by as much as 100 percent or more for cells having cloud bases > 16 °C. As is the case in Texas, these increases have been produced by broader cells with longer durations. Vertical cell growth of the S cells has been small relative to the growth of the NS cells and does not, therefore, appear to be a requirement for the rain increases. An important finding is that AgI-treated cells in both Texas and Thailand produce more rainfall than non-seeded cells having the same echo top height. How this increase might take place is addressed extensively in the conceptual model (see part I).

It is also possible, however, that the vertical growth of the S cells may have been underestimated by the S-band radar operative in Thailand. If the seeding effects proceed as postulated in the conceptual model, much of the water in the cloud following AgI seeding will be intercepted by a graupel formation, growth, and storage region within the cloud, leaving only small ice crystals for transport to cloud top. This occurrence would result in lesser reflectivity at cloud top than might be the case with the NS clouds, resulting in an underestimation of the true cloud top by an S-band radar that is not particularly sensitive to small ice particles. Visual inspection of the clouds in real time and on video tape suggests a more stratified glaciated structure of the tops of the S cells relative to those that have not been seeded.

Unintended biases may play a larger role in the Thai results to date than they have in Texas. About one-third of the Thai cells existed on radar prior to their real or simulated AgI treatment. In that subsample, the S cells covered somewhat more area and had slightly larger rain fluxes than the NS cells that existed on radar prior to treatment. This finding does not, however, appear to be a bias that favors more S rainfall subsequently. If anything, large pre-treatment rainfall is a negative indicator for the rainfall to be expected subsequently.

The results for the 14 experimental units (7 S and 7 NS) for which analysis is possible are consistent with a positive effect of seeding. The natural variability is great and the results are highly sensitive to removal of the wettest unit from each of the S and NS samples.

The Thai cold cloud experiments appear to be on the right track, and the obvious recommendation is that they continue. The present design appears to be well suited for the continuation, considering the progress that has been made so far.

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APPENDIX C

Development of an Objective Technique for Forecasting Convective Cloud-Top Heights in Thailand

C.1 Introduction

During the period from early 1988 through 1993, Reclamation (Bureau of Reclamation) and the BRRAA (Bureau of Rainmaking Research and Agricultural Aviation) worked together on Thailand's AARRP (Applied Atmospheric Resources Research Program). The study area for the AARRP was located in the hilly terrain of northwestern Thailand, where runoff from significant rainfall flows into Bhumibol Reservoir. The AARRP's field operations center was located at the TMD (Thai Meteorological Department) regional center in Chiang Mai.

As part of the AARRP, an S-Band Doppler weather surveillance radar system was installed at a site near Omkoi, about 120 kilometers south-southwest of Chiang Mai. Upper-air soundings were made at both the Omkoi radar site and the TMD facility in Chiang Mai.

Indices computed from early morning soundings were found to give good indications of the occurrence of afternoon convective activity for at least two weather modification research experiments in the U.S. (Hartzell and Jameson, 1981; Scott and Huff, 1986). It was believed that these indications might also apply to the AARRP study area in Thailand.

Both dynamic cold cloud seeding and hygroscopic warm cloud seeding exploratory experiments were attempted from April 15 to August 15, 1993. A preliminary experimental day declaration was made each morning based on computer analyses of the 0700 LST (0000 GMT) sounding data from Chiang Mai and Omkoi. The criteria for declaring either a cold or warm cloud experimental day were listed in the "AARRP Field Operations Plan for the 1993 Exploratory Experiments."

The sounding indices used were found to be unreliable for making experimental day declarations. Consequently, following the 1993 AARRP field season, the sounding data taken at 0700 LST and the radar echo tops observed between 1200 and 1800 LST were used in a study to develop an objective technique for forecasting convective cloud-top heights. This technique was expected to improve the warm or cold cloud seeding experimental day declarations.

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C.2 AARRP Radar Data

The AARRP Doppler weather surveillance radar system is an Enterprise Electronics Corporation model DWSR-88S, with the following principal characteristics:

• Frequency	2.7-2.9 GHz
• Wavelength	10.8 cm
• Peak power	500 kW
• Pulse duration	2 µs (ref.), 0.8 µs (vel.)
• PRFs	250 s^{-1} (ref.), 600/1000 s^{-1} (vel.)
• MDS	-106 dBm
• Antenna diameter	6.1 m (beamwidth approximately 1.2°)

During nonoperational periods, the AARRP radar system was operated in a surveillance mode, which was composed of a base scan every 5 minutes and a complete volume scan every 30 minutes. Complete volume scans were made every 5 minutes during operational periods. The radar data were automatically recorded on tape.

The radar data were later processed by Dr. Daniel Rosenfeld, under a Reclamation contract with Woodley Weather Consultants. Using software he developed, Dr. Rosenfeld derived PDFs (probability density functions) in 3-hour blocks for echo reflectivities and heights, for 10- by 10-kilometer squares within a 150-kilometer range of the radar. The echo top was defined as the highest echo exceeding 12 dBZ. The PDFs contained 16 1-kilometer classes of echo height (from 3 to 18 kilometers).

Reclamation's scientific advisor on the AARRP, Dr. Bernard Silverman, wrote a FORTRAN program to use the PDF data files to obtain estimated rainfall and echo top heights. The procedure used to determine echo top heights was:

- Summarize the PDFs of height for each of the 16 classes.
- Calculate the total counts.
- Calculate a running sum of the counts.
- Select a desired percentile level, e.g., 95.

The height at which the running sum divided by the total exceeds 0.95 then becomes the echo top height. The 0.95 level was used to eliminate isolated counts.

The radar PDF data were used to select target areas for Phase 2 of the AARRP. The area selected for this study, which included the eastern two Phase 2 target areas, was a 6,000-square-kilometer area located 60 to 160 kilometers south of Chiang Mai and 30 to 90 kilometers east of the radar site.

C.3 Upper-air Sounding Data

Good data were essential for use in this study. All of the soundings were carefully quality controlled; only soundings that had good data to at least the 150-millibar level were used.

During the 1993 AARRP field season, some problems were noted with the TMD's 0000 GMT (0700 LST) Chiang Mai soundings. On some days, the Chiang Mai soundings appeared to be either significantly too warm or too cold; the problem became more pronounced above the 500-millibar level. The Chiang Mai soundings were compared to the Omkoi soundings, when available, and also to Chiang Mai soundings made 1 day on either side of the day being evaluated. Table C.1 shows an example of an comparison between Chiang Mai and Omkoi for May 26, 27, and 28, 1993. A corresponding Omkoi sounding was not always available.

All days with questionable Chiang Mai data were dropped from this study. The resulting data set consisted of 54 days for which both a good 0000 GMT Chiang Mai sounding and AARRP radar data were obtained.

C.4 Sounding Analysis Programs

Two sounding analysis programs were run daily. One of the programs was Reclamation's GPCM (Great Plains Cumulus Model), which was developed for use on weather modification research projects located in the Great Plains of the United States. The second program, ANALYZR, was also developed by Reclamation.

C.4.1 GPCM description

GPCM is a simple, one-dimensional, steady-state parcel model that predicts maximum cloud tops; the estimates depend upon the initial updraft radius, the height of the CCL (convective condensation level), and the entrainment constant used. The model updraft radii that best compare with aircraft observations near cloud base are 1.0 to 3.0 kilometers (in 0.5-kilometer intervals). The model updraft radius varies with height to satisfy mass continuity.

The height of the CCL depends upon the mixing depth selected and the amount of low-level moisture available. Because of the tropical climate in Thailand, a 50-millibar mixing depth was used in the GPCM. The accuracy of the input data is critical. Even a small error in the surface dewpoint can cause significant changes in the height of the CCL and estimated cloud-top heights.

Entrainment (E) is simulated in GPCM by the relationship:

$$E = C/R$$

where C is a constant and R is the updraft radius.

The value used for C in GPCM in Thailand has been 0.150, which was the same value as used on Project Cloud Catcher (Hirsch, 1971). Matthews (1981) used a value of 0.200 for C in a study of data from three U.S. High Plains sites.

Table C.1. - Comparison of CM (Chiang Mai) and OK (Omkoi) temperatures (°C) at standard pressure levels.

P Lvl (mb)	05/26/93 CM - OK = Diff	05/27/93 CM - OK = Diff	05/28/93 CM - OK = Diff
150	-66.5 -65.5 -1.0	-53.7 -64.3 10.6	-70.3 -66.3 -4.0
200	-50.5 -50.7 0.2	-41.9 -49.7 7.8	-54.9 -51.3 -3.6
250	-38.1 -38.3 0.2	-32.3 -38.1 5.8	-41.9 -39.7 -3.2
300	-29.3 -29.5 0.2	-24.7 -28.7 4.0	-32.5 -28.7 -3.8
400	-15.5 -13.7 -1.8	- 9.9 -14.5 4.6	-16.3 -13.5 -2.8
500	- 3.7 - 4.5 0.8	- 2.7 - 3.7 1.0	- 5.7 - 3.7 -2.0

05/26/93: Good agreement.
05/27/93: CM way too warm above the 500-millibar level.
05/28/93: CM colder than OK, but this occurrence is usually observed in the data set.

C.4.2 ANALYZR description

The ANALYZR program decodes and performs a thermodynamic analysis of a sounding data file. The program calculates precipitable water for three depths, cloud base information using a 50-millibar mixing depth for computing the CCL, and various stability indices, e.g., the Lifted index and the Showalter index. CAPE (convective available potential energy) values for 1.0- and 2.0-kilometer updraft radii were included and calculated following Zhang and McFarlane (1991). Also included was the potential buoyancy value used by Czys and Scott (1993) during the 1989 PACE (Precipitation Augmentation for Crops Experiment) cloud-seeding experiment.

C.5 Development of Objective Forecasting Technique

C.5.1 GPCM calibration

Project scientists who used the output from GPCM on a daily basis observed that this simple model usually overestimated the natural maximum cloud-top heights. Uncertainty also existed as to which updraft radius provided the best estimate. Consequently, it was desirable to calibrate GPCM, and at the same time try to use the output from the model in an objective technique to forecast afternoon convective cloud-top heights using the 0700 LST morning soundings.

The procedure used to calibrate GPCM was to vary the entrainment constant for different updraft radii and compare the estimated natural cloud-top heights with the 95th percentile radar echo tops (RETE95) observed within the study area. Seven different constants, ranging from 0.100 to 0.250, were used with four updraft radii, viz., 1.5, 2.0, 2.5, and 3.0 kilometers.

The model was run with sets of sounding input data files from both Chiang Mai (EL 307 m) and the Omkoi radar (EL 1126 m). The best results were obtained with the Chiang Mai data because: 1) the higher elevation of the Omkoi site results in important low-level moisture not being observed; and 2) the hilly terrain surrounding the Omkoi site causes topographic effects, especially during the monsoon season. Omkoi soundings do provide useful information on stability, moisture distribution, and wind flow above the 850-millibar level.

The 54-sounding data set was divided into premonsoon and monsoon subsets; however, the smaller subsets produced unstable results. Table C.2 shows the results from statistical correlation and linear regression analyses for the combined 54-sounding data set from Chiang Mai.

The most significant finding from the correlation analysis is that the entrainment constant should be increased with increasing cloud updraft radius. Figure C.1 shows an example of the GPCM output for varied entrainment constants. The regression plot for the 54-day Chiang Mai sample of GPCM estimated 2-kilometer updraft radius cloud tops with observed 95 percentile radar echo tops is shown on figure C.2; the dashed lines are the 95-percent confidence limits on individual predicted values. For the 54-day sample, the mean 2-kilometer cloud top value from GPCM was 10.1 kilometers, and ranged from 2.1 to 15.1 kilometers.

Table C.2. - Combined Chiang Mai GPCM cloud tops with RETE95.

Radius (km)	Entrainment Constant 0.100	0.125	0.150	0.175	0.200
1.50					
CORR	0.31	0.51	0.50	0.47	0.46
RMSE	1.32	1.20	1.20	1.22	1.24
YINT	7.49	6.99	7.08	7.30	7.21
2.00					
CORR	0.24	0.31	0.51	0.50	0.50
RMSE	1.35	1.32	1.19	1.20	1.20
YINT	7.70	7.52	6.92	7.11	7.13
2.50					
CORR	0.22	0.32	0.28	0.49	0.47
RMSE	1.36	1.31	1.33	1.21	1.23
YINT	7.49	7.22	7.66	6.99	7.26
3.00					
CORR	0.20	0.20	0.32	0.28	0.46
RMSE	1.36	1.36	1.32	1.33	1.23
YINT	7.56	7.69	7.25	7.75	7.14

CORR = correlation
RMSE = root-mean-square error
YINT = Y-axis intercept

USBR GREAT PLAINS CLOUD MODEL - GPCM SUMMARY OUTPUT

STATION: CM DATE: 8/16/93 TIME: 0 GMT

UPDRAFT RADIUS (KM)	N/M	CLD TOP HGT. (KM)	CLD TOP TEMP (C)	MAX UPDR (M/S)	AT HGT. (KM)	AT TEMP (C)	MAX REFL (DB)	AT HGT. (KM)	EFFICIENCY PRECIP (PCT)	EFFICIENCY COND. (PCT)	DYN POT (KM)
ENTRAINMENT CONSTANT = 0.100											
1.00	NAT	10.2	-31.0	12.1	6.5	-6.7	59.8	8.2	27.8	95.4	
	MOD	11.0	-37.6	12.1	9.0	-21.7	59.8	6.7	22.8	97.6	0.80
ENTRAINMENT CONSTANT = 0.125											
1.50	NAT	10.5	-32.7	12.4	6.5	-6.5	61.3	8.2	28.9	96.1	
	MOD	11.6	-42.1	14.3	9.3	-22.9	62.2	6.7	27.3	98.4	1.11
ENTRAINMENT CONSTANT = 0.150											
2.00	NAT	11.3	-39.4	12.5	6.5	-6.4	62.4	8.2	34.7	97.9	
	MOD	12.2	-47.4	15.6	9.5	-24.4	63.5	6.7	34.7	99.1	0.90
ENTRAINMENT CONSTANT = 0.175											
2.50	NAT	11.9	-44.5	12.5	6.5	-6.3	63.3	8.2	40.0	98.8	
	MOD	12.5	-50.2	16.2	9.5	-24.2	64.3	6.7	39.0	99.3	0.63
ENTRAINMENT CONSTANT = 0.200											
3.00	NAT	12.2	-47.1	12.4	6.5	-6.3	63.9	8.2	43.5	99.1	
	MOD	12.8	-53.1	16.6	9.5	-24.0	64.9	6.7	45.4	99.5	0.65

MIXING DEPTH USED FOR CCL	50. MBAR
CLOUD BASE PRESSURE (CCL)	880. MBAR
CLOUD BASE HEIGHT (CCL)	1.2 KM 3864. FT
CLOUD BASE TEMPERATURE (CCL)	20.1 C
SUB CLOUD MIXING RATIO	17.0 G/KG
SURFACE CONVECTIVE TEMP.	28.4 C 83. F

Figure C.1. - Example of revised GPCM output (Chiang Mai, August 16, 1993).

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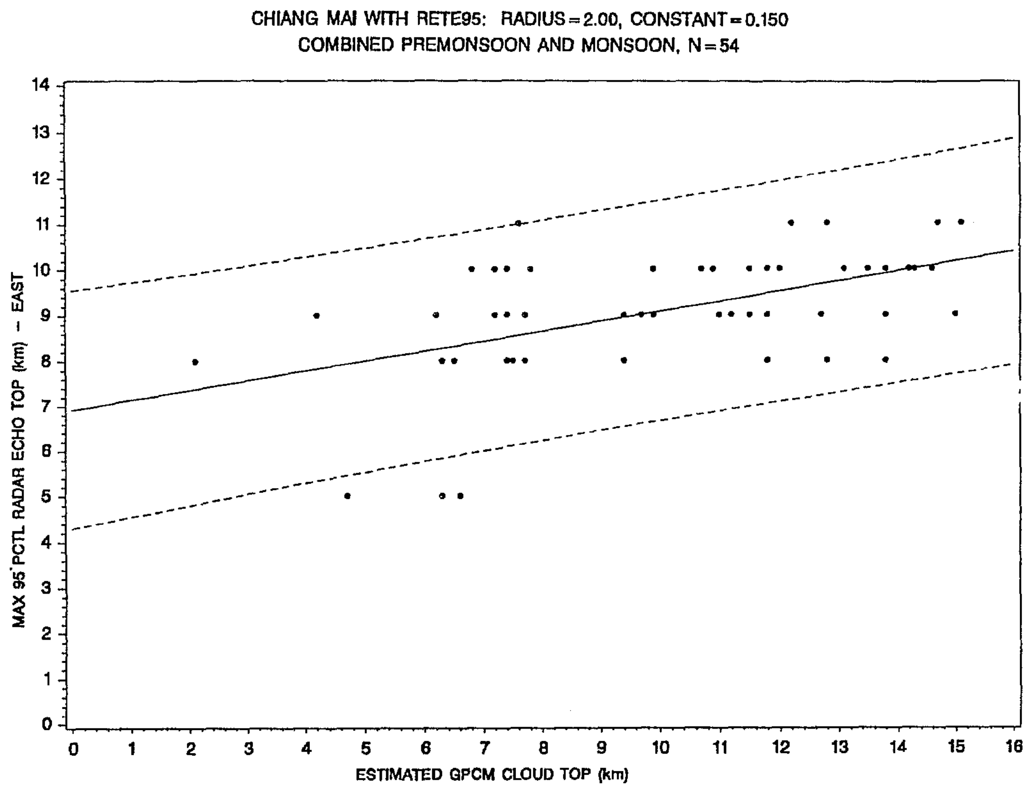

Figure C.2. - Linear regression plot for updraft radius of 2 kilometers.

C.5.2 MLR analysis

An MLR (multiple linear regression) analysis was run using 23 sounding variables obtained from ANALYZR and the estimated cloud top from GPCM for the 2.0-kilometer updraft radius with $C = 0.150$. The variables used are listed in table C.3. A correlation analysis giving the sample correlations between variables was also obtained.

The 24 variables were compiled for each of the 54 Chiang Mai 0700 LST sounding data files and used in the MLR analysis; RETE95 was the dependent variable. All of the variables in the model were significant at the 0.15 level. Table C.4 lists the mean, standard deviation, minimum and maximum values, and the sample correlation with RETE95 for the 24 variables. The negative correlations are variables that are inversely correlated with RETE95. Also listed in the table are inter-variable sample correlations for the five selected variables with the highest correlation with RETE95.

Table C.3. - Variable definitions used in the MLR analysis.

Variable	Definition
PW850	Precipitable water surface to 850 millibars (inches)
PW700	Precipitable water surface to 700 millibars (inches)
PW500	Precipitable water surface to 500 millibars (inches)
GPCM2	GPCM estimated cloud top height (2-kilometer radius updraft)
RH10K	Average relative humidity, surface to 10,000 feet
RH18K	Average relative humidity, 10,000 to 18,000 feet
RHCCL	Relative humidity at the CCL
ZFBASE	Cloud base / CCL height (feet)
TBASE	Cloud base / CCL temperature (°Celsius)
LI100	Lifted Index - 100-millibar-layer adiabatic
LI50	Lifted Index - 50-millibar-layer mean values
SHOWI	Showalter Index (computed using 850-millibar T & Td)
TOTOI	Total Totals Index
KIND	K-Index
PBIND	Potential Buoyancy Index
TDCCL5	CCL temperature minus 500-millibar temperature
CAPE11	Convective Available Potential Energy (AO=0.10, RAD=1.0)
CAPE12	Convective Available Potential Energy (AO=0.15, RAD=2.0)
AWS1	Average wind speed 1,000 - 5,000 feet (knots)
AWS2	Average wind speed 5,000 - 10,000 feet (knots)
AWS3	Average wind speed 10,000 - 15,000 feet (knots)
AWS4	Average wind speed 20,000 - 25,000 feet (knots)
DSHEAR	Absolute wind direction shear, AWD1 - AWD4 (degrees)
SSHEAR	Absolute wind speed shear, AWS1 - AWS4 (knots)
RETE95	Measured radar echo tops, 95 percentile (kilometers)

Table C.4. - Chiang Mai sounding parameters—premonsoon and monsoon combined.[1]

Variable	Mean	Std. Dev.	Minimum	Maximum	*R/RETE95*
PW850	0.74	0.06	0.59	0.87	0.36*
PW700	1.40	0.14	0.99	1.68	0.30
PW500	1.84	0.24	1.13	2.21	0.27
GPCM2	10.09	3.21	2.10	15.10	0.51*
RH10K	81.64	10.77	52.00	96.20	0.26
RH18K	72.85	16.48	24.00	94.70	0.23
RHCCL	83.24	12.00	50.20	96.80	0.20
ZFBASE	4892.00	1725.00	2582.00	8791.00	-0.24
TBASE	18.58	2.38	13.50	22.10	0.29
LI100	-2.25	1.65	-6.60	1.30	-0.39*
LI50	-1.40	1.70	-5.80	2.60	-0.37*
SHOWI	-0.56	1.92	-5.10	3.70	-0.33
TOTOI	45.20	3.36	38.20	54.40	0.27
KIND	36.15	3.48	26.50	44.10	0.35
PBIND	3.04	1.71	-0.80	7.60	0.25
TDCCL5	23.90	2.12	17.80	28.40	0.43*
CAPE11	157.33	125.70	8.30	541.80	0.31
CAPE12	196.34	181.86	-7.90	786.20	0.33
AWS1	4.48	2.37	0.50	10.80	-0.15
AWS2	11.41	5.72	2.20	25.00	-0.11
AWS3	11.37	5.83	2.40	24.70	-0.23
AWS4	19.99	15.26	2.90	88.00	-0.14
DSHEAR	84.44	75.58	1.00	272.00	0.08
SSHEAR	15.83	15.00	0.20	84.30	-0.14
RETE95	9.13	1.37	5.00	11.00	1.00

* Selected Sample Correlation Coefficients (R)

	PW850	*GPCM2*	*LI100*	*LI50*	*TDCCL5*
PW850	1.00	0.16	-0.42	-0.57	0.79
GPCM2	0.16	1.00	-0.46	-0.41	0.33
LI100	-0.42	-0.46	1.00	0.92	-0.69
LI50	-0.57	-0.41	0.92	1.00	-0.78
TDCCL5	0.79	0.33	-0.69	-0.78	1.00

[1](sample size = 54; R = sample correlation coefficients)

The primary results from MLR were:

Step 1: *GPCM2* model $R^2 = 0.25$
Step 2: *PW850* model $R^2 = 0.34$
(Correlation between *GPCM2* and *PW850* = 0.16

$Y = 1.95 + 6.98\ PW850 + 0.19\ GPCM2$

1X5

The first variable selected in the MLR analysis was the estimated cloud top height from the model (*GPCM2*). The variable selected in step 2 was the precipitable water from the surface to the 850-millibar level (*PW850*), indicating the importance of low-level moisture. The above equation gave a mean *Y* value for predicted radar echo tops (Predict) of 9.1 kilometers; values ranged from 7.7 to 10.9 kilometers. The MLR plot for this 54-sounding sample is shown on figure C.3.

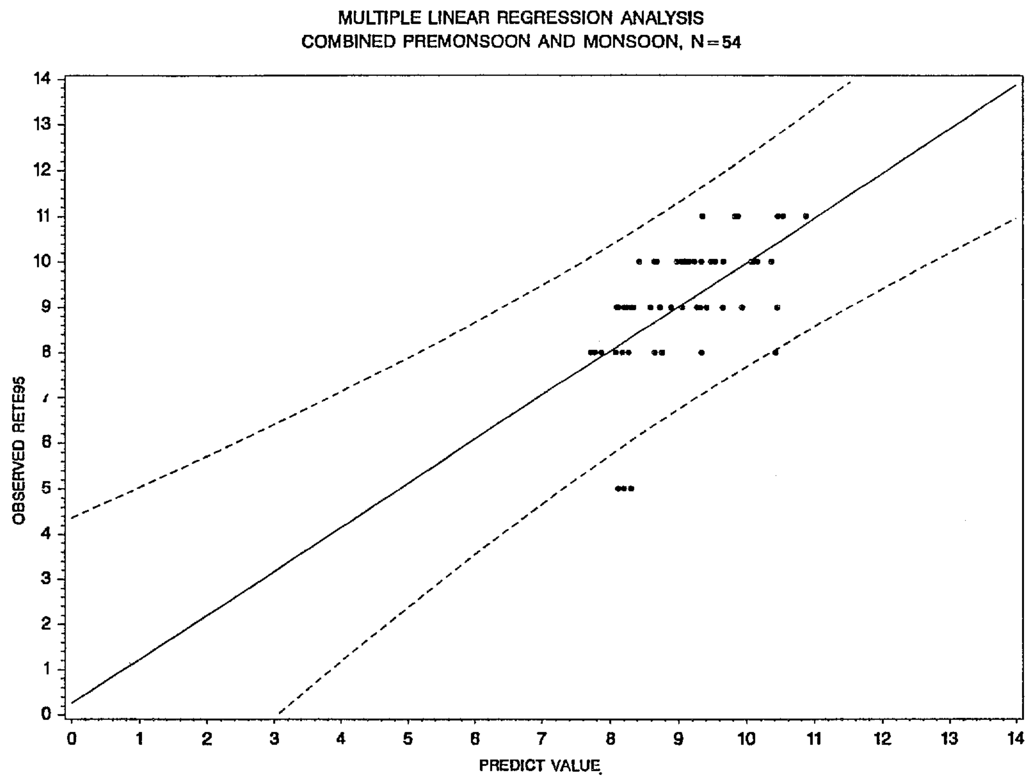

Figure C.3. - MLR plot for Predict values with RETE95.

C.5.3 Findings

It was anticipated that the objective technique developed could be used to preselect days with only warm cloud tops from days with cold convective cloud tops. The -5 °C temperature was used as the cutoff for warm cloud tops; the mean height of the -5 °C temperature during the 1993 field season was around 5700 meters.

An interesting finding was that for the 54-day sample, only 3 days had RETE95 heights lower than 5.7 kilometers. On the other 51 days, RETE95 ranged from 8.0 to 11.0 kilometers; the mean was 9.1 kilometers. However, even on the 51 days when these radar echoes from cold cloud precipitation were observed, many smaller convective clouds that were suitable for warm cloud seeding probably resided within the study area.

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Table C.5 lists the frequency of the residuals (RETE95 - Predict) in 1-kilometer class intervals from the MLR analysis. The residuals ranged from -3.3 to 1.6 kilometers. The mean of the absolute residual values was 0.81 kilometer; 41 of the 54 days (76%) had a residual of less than 1.0 kilometer.

Table C.5. - Frequency of residuals.

Interval (km)	Negative	Positive	All
0.0 - 1.0	17	24	41
1.0 - 2.0	2	7	9
2.0 - 3.0	1	0	1
3.0 - 4.0	3	0	3
Totals	23	31	54

C.6 Conclusions and Recommendations

Conclusions:

1. For the 54-day sample, 95 percent of the days had RETE95 heights greater than about 8.0 kilometers; consequently, the MLR analysis equation given in section C.5.2 cannot be used for selecting days with only warm convective clouds.

2. Even with a much larger data set sample, it is believed that using the 95th percentile radar echo tops would not result in an objective technique that could be used operationally to make reliable warm or cold cloud seeding experimental day declarations.

3. Using the MLR equation will provide a better, objective estimate for convective cloud tops expected over the AARRP's study area than the maximum natural cloud-top height estimates from GPCM. (Compare figs. C.2 and C.3).

4. Based on the 54-day sample, the observed RETE95 heights should be within 1.0 kilometer of the Predict heights from the equation about 75 percent of the time. Consequently, the AARRP operations director should have a better indication of the convective cloud intensity to expect during the afternoon.

Recommendations:

1. Conduct an operational test using the equation obtained from the 54-day sample and compare with observed 95 percentile radar echo tops over the eastern target areas.

2. Analyze the radar echo top data for the 54-day sample using different percentiles of observed radar echo tops; reduce the percentile value until the percentile is found that eliminates the higher echoes from cold clouds. (The percentile values should be reduced until only radar tops equal to or less than 6.0 kilometers remain).

3. Select the percentile of observed radar echo tops from step 2 that produces representative samples of days with warm and cold cloud tops. Rerun the MLR analysis on the 54-sounding sample data set using radar echo tops at this percentile as the dependent variable.

4. Redo the correlation and MLR analyses using a larger sample size. A larger sample of quality Chiang Mai 0000 GMT soundings is needed to increase the stability of the statistical analyses; this larger sample would also allow analyses of premonsoon and monsoon data subsets. Only days that also have good AARRP radar data can be included in this larger sample.

C.7 References

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APPENDIX D

Seeding Strategies for the Warm Cloud Demonstration Project

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D.1 Introduction

A key goal in the design of the warm cloud seeding demonstration project is the selection of a hygroscopic chemical seeding strategy that is scientifically, logistically, and economically feasible. A numerical cloud model that is capable of simulating cloud and precipitation development under natural and seeded conditions was used in the search for a viable warm cloud seeding strategy. The numerical cloud model provided an inexpensive means of screening numerous candidate warm cloud seeding strategies to identify those that are most promising scientifically (World Meteorological Organization, 1981). Other investigators who used a model for this purpose include Biswas and Dennis (1972), Klazura and Todd (1978), Silverman and Kunkel (1970), Johnson (1980), Rasmussen et al. (1989) and Tzivion et al. (1994).

Of the most scientifically promising seeding strategies found in these model experiments, the one that best meets the logistical and economic feasibility requirements is then recommended for incorporation in the design of the warm cloud seeding demonstration project.

D.2 The Numerical Cloud Model

The one-and-one-half-dimensional, time dependent, detailed microphysical model originally developed by Silverman and Glass (1973), as extended by Nelson (1979) to include ice processes, and further updated by Silverman to include ice multiplication processes and a variety of hygroscopic chemical seeding options, was used to test the relative effectiveness of a wide range of seeding scenarios. This model is referred to by its creators as the HAMOD model. HAMOD is most realistic in simulating the precipitation initiation process in clouds and, because of its dimensionality limits, becomes less realistic in simulating the further evolution of the precipitation process; nevertheless, the difference between natural and seeded precipitation is believed to be a realistic measure of the relative effectiveness of the seeding scenarios (referred to herein as $S(H)/S(N)$). A further measure of the relative effectiveness of the hygroscopic chemical seeding scenarios was obtained by comparing the results of the hygroscopic chemical seeding with that of water drop seeding for equivalent seeding particle sizes and seeding dosages (referred to herein as $S(H)/S(W)$); water particle seeding by itself is capable of increasing precipitation from warm clouds (Braham et al., 1957; Nelson, 1971).

The cloud in HAMOD is modeled as a radially symmetric cylindrical column of air with a time-independent radius of prescribed size in an environment at rest. The model combines the vertical equation of motion, the first law of thermodynamics, the equation of mass continuity, and equations of conservation for water vapor, cloud droplets, and raindrops. All quantities are thus functions of both vertical location and time. Entrainment in the cloud occurs through both turbulent and dynamic processes. Turbulent entrainment occurs on the sides of the cloud as it ascends and is proportional to the updraft velocity and eddy diffusion coefficient, and inversely proportional to the square of the cloud radius. The eddy diffusion coefficients for heat, water vapor, particles, and momentum are prescribed, time-independent, and assumed to equal. Dynamic entrainment occurs in order to satisfy the constraints of mass continuity imposed by assuming a constant cloud radius. Thus, below the level of updraft maximum, environmental air is entrained into the cloud and cloud air is detrained into the environment above the level of updraft maximum in order to keep the cloud radius constant.

HAMOD effectively models a single cell cumulus cloud in an environment with no wind shear, the so called "one puffer" cloud. Clouds of this type do exist, especially among warm, relatively shallow tropical clouds. In these types of clouds, water loading or negative buoyancy caused by the drag of condensed water is a major constraint on the time duration of the cloud and, therefore, the cloud's precipitation development, as will be demonstrated later. In such clouds, the time available for precipitation development is relatively short, and seeding that causes the acceleration of the initiation and/or development of precipitation is postulated to result in an increase in precipitation efficiency and rainfall with respect to that from the nonseeded cloud. Hygroscopic seeding is postulated to affect this chain of physical events by accelerating, if not improving, the coalescence process.

Starting with a cloud condensation nucleus spectrum, the formation and growth of cloud droplets and rain by condensation, coalescence, and drop breakup are modeled in detail for 67 logarithmically spaced size categories that span a particle radius from 2 to 4040 micrometers. HAMOD uses a special form of the condensation growth equation that is particularly accurate for dry and highly concentrated hygroscopic particles. The nucleation, vapor depositional growth, and collisional growth of ice crystals is modeled in detail for 67 logarithmically spaced size categories spanning a particle radius from 14 micrometers to 28 millimeters. The sedimentation of both water and ice particles is driven by the combination of particle terminal velocity and updraft velocity.

The actual model calculations of natural cloud development (base runs) proceeded in the following manner:

1. An environmental sounding was specified and interpolated for all the model grid levels. The potential temperatures in lower levels of the sounding were set equal to the cloud base potential temperature as determined by the one-dimensional, steady state GPCM (Great Plains Cumulus Model) (Hirsch, 1971). The relative humidity in the sub-cloud layer was unchanged. Soundings representative of the proposed target area were used in all cases.

2. A vertical velocity pulse on the order of 3 meters per second was introduced in the lowest level of the model to trigger the initiation of the cloud. The time duration that this pulse was maintained was prescribed, usually about 600 seconds. The level at which the relative humidity exceeded 100 percent was defined as cloud base. As the cloud developed, the cloud base level was permitted to raise or lower in response to the resulting changes in the state variables. Using these pulse characteristics resulted in cloud base height and temperatures which agreed closely with those from GPCM, the small differences being caused by the fact that HAMOD includes entrainment in the sub-cloud layer and GPCM does not.

3. A dry nucleus spectrum, with up to 20 logarithmically spaced mass classes, was then activated. The nuclei were assumed to be sodium chloride particles. The radius attained by each of the nuclei at cloud base was determined by condensational growth, assuming that the air parcel rose from the ground through the temperature and humidity field in the subcloud layer at the average subcloud layer velocity. The resulting droplet spectrum was then collapsed into the 67 water categories and inserted at the cloud base level. All the cloud droplets inserted at cloud base were assumed to have the same, relatively small nucleus mass; however, the nucleus mass for the maritime nuclei spectra was larger than that for the more continental nuclei

spectra. As a result of this assumption, further condensational growth on the larger cloud droplets was underestimated initially; however, the amount of underestimation rapidly diminished and disappeared as these droplets grew by condensation and coalescence.

4. The model equations were then integrated in time using a time step calculated to be short enough to maintain numerical stability. The calculations were terminated when the cloud hydrometeor fields indicated that the cloud ceased to exist or when the allotted CPU time was exhausted, whichever came first.

The model calculations of seeded cloud development (seeded runs) proceeded in the following manner:

1. The HAMOD model has a feature which enables a model base run to be restarted at any model time to either a) extend the time history of the base run if it did not run to completion before, or b) introduce seeding at any specified time in the base run to obtain the life history of the seeded cloud (seeded run). A restart run in the middle of a base run without seeding would merely duplicate the initial base run. For seeded runs, the base run was restarted just prior to the time of seeding.

2. At the specified seed time, hygroscopic seeding particles are injected into the model at the specified seeding level. The hygroscopic seeding particles may be either dry or saturated solution drops; either sodium chloride, calcium chloride, ammonium nitrate, urea, or any hygroscopic chemical with externally specified physical-chemical properties, and either monodisperse or polydisperse. Seeding with water drops and seeding at more than one time and/or more than one model level may also be specified.

3. The radius attained by each of the seed particles was determined by condensational growth for 60 seconds, using the thermodynamic conditions at the seed level. The resulting seed drop spectrum was then collapsed into the 67 water categories and inserted at the seed level. All the seed droplets inserted at seed level were incorporated into the existing cloud droplet spectrum and were assumed to have the same, relatively small sodium chloride nucleus mass as the cloud droplets. As a result of this assumption, further condensational growth on the seed particles was underestimated; however, because further development of the hydrometeor spectrum was then largely dominated by coalescence, the impact of this underestimation is expected to have little impact on the results.

4. The model equations were then integrated in time as before and terminated when the cloud hydrometeor fields indicated that the cloud ceased to exist, or when the allotted CPU time was exhausted, whichever came first.

D.3 Scope of the Hygroscopic Seeding Experiments

The hygroscopic seeding experiments were carried out in three phases. In phase 1, a series of experiments was conducted using a single atmospheric sounding to test the relative effectiveness of various hygroscopic chemicals dispensed as dry particles and saturated solution drops, of monodisperse versus polydisperse seeding particle distributions, of cloud base versus cloud top seeding, of various seeding rates, and of various seeding times after cloud formation. In addition, the relative effectiveness of seeding a cloud with and without water loading was tested.

Seeding experiments were conducted in phase 2 to test the relative effectiveness of seeding warm versus cold clouds with the most promising seeding strategies from the phase 1 experiments. In addition, the effect of various input nuclei spectra on natural and seeded rainfall was explored. The relative effectiveness of subcloud layer seeding with hygroscopic flares, as used in South Africa (Mather and Terblanche, 1992), was also explored.

In phase 3 of the seeding experiments, the most promising seeding strategies from phases 1 and 2 were screened, and the most practical of these were applied to 10 additional warm cloud soundings and 5 additional cold cloud soundings taken at Chiang Mai during 1993. The aim of these studies was to explore the range of seeding results and to see if they could be related to characteristics of the unseeded clouds.

D.3.1 Atmospheric Soundings

The sounding used in phase 1 was taken at 0600 GMT on July 20, 1979, at Port Blair, India (fig. D.3.1). Port Blair soundings were used in the first Thailand model study (Medina et al., 1989), and this one was found to be representative of atmospheric conditions on many days in the proposed target area. The cloud that the model produced from this sounding had a cloud base temperature of 20 °C, a cloud depth of 2200 meters, lasted for 33 minutes, and produced 0.0024 millimeters of rain on the ground.

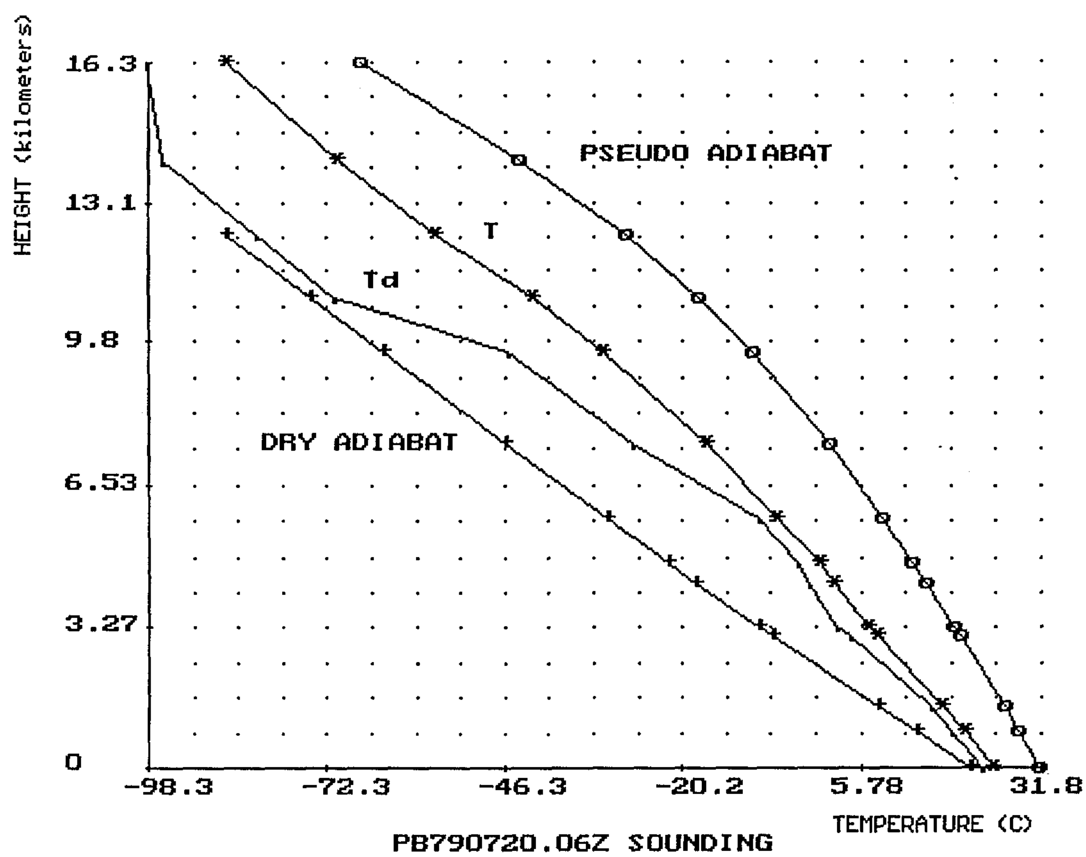

Figure D.3.1. - Atmospheric sounding taken at Port Blair, India, July 20, 1979, 0600 GMT.

The two soundings used in phase 2 were taken during 1992 at Chiang Mai, that is, 0000 GMT on August 10, 1992, and 0000 GMT on August 22, 1992 (figs. D.3.2 and D.3.3). These soundings resulted in the development of a typical cold and warm cloud, respectively.

The warm and cold cloud soundings used in phases 2 and 3 are listed in table D.3.1. Table D.3.1 shows that, for the warm clouds, the rain produced is directly proportional to the rain efficiency of the cloud (defined as rain on ground divided by total water condensed by the cloud), and generally increases with increasing cloud depth. This process is typical of a warm cloud where condensation-coalescence is the dominant precipitation mechanism. For the cold clouds, the same relationships appear to generally hold. For these clouds, the condensation-coalescence is still active and is responsible for the initiation of rain. The ice process, influenced by the earlier freezing of the large drops produced by condensation-coalescence, then takes over.

Table D.3.1. - List of Chiang Mai soundings used in the phase 2 and 3 seeding experiments and general characteristics of the model clouds that result before seeding. Warm and cold clouds are listed separately in ascending order of rain produced.

Sounding	Cloud Base Temp (°C)	Cloud Depth (m)	Cloud Duration (min)	Rain Efficiency (%)	Rain Amount (mm)
A. Warm Clouds					
CM930826	19.5	1710	75	0.00000	0.00000
CM930527	20.8	1420	75	0.00000	0.00000
CM930422	18.0	1200	75	0.00001	0.00000
CM930814	20.8	1930	75	0.00021	0.00001
CM930809	20.4	2970	75	0.00677	0.00099
CM930815	20.0	2730	75	0.00788	0.00121
CM920822	18.8	2800	50	0.08481	0.01011
CM930807	19.8	2930	70	0.08761	0.01582
CM930816	20.1	3230	39	0.21288	0.04485
CM930821	19.3	2860	75	0.28812	0.04672
CM930813	20.4	3450	47	0.74997	0.13711
B. Cold Clouds					
CM930507	16.4	4090	59	0.0004	0.00005
CM930425	16.1	6480	55	1.1630	0.84784
CM930808	21.0	5260	64	11.5970	4.98830
CM930806	19.5	5600	65	16.2250	7.72951
CM920810	21.1	7330	50	19.0460	10.14810
CM930606	21.3	7530	56	8.9860	14.42210

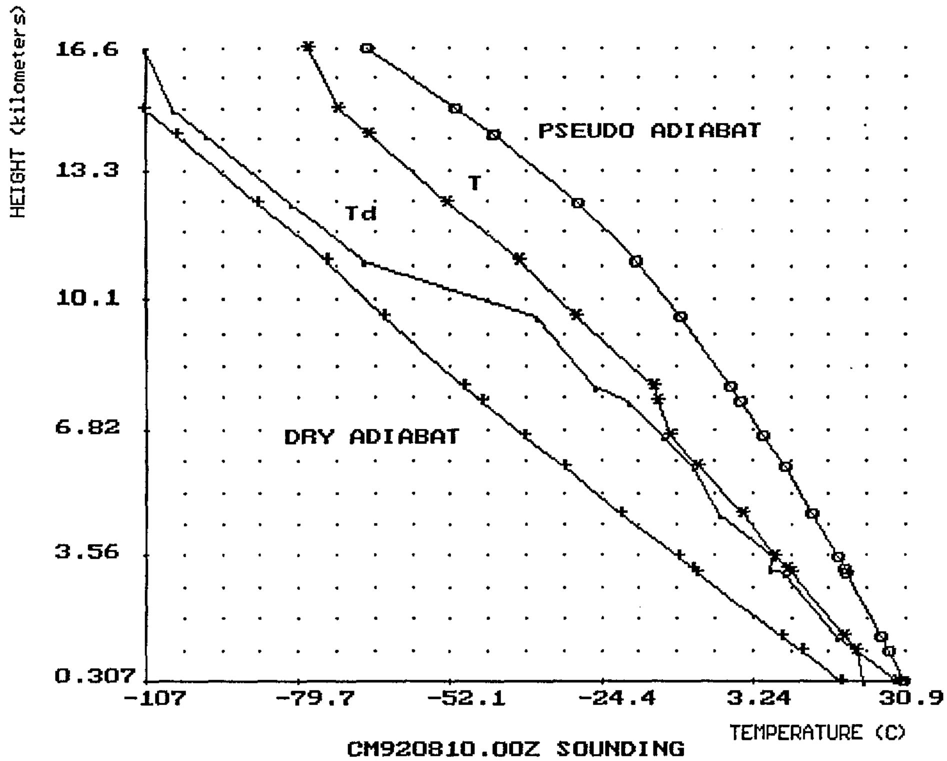

Figure D.3.2. - Atmospheric sounding taken at Chiang Mai, Thailand, August 10, 1992, 0000 GMT.

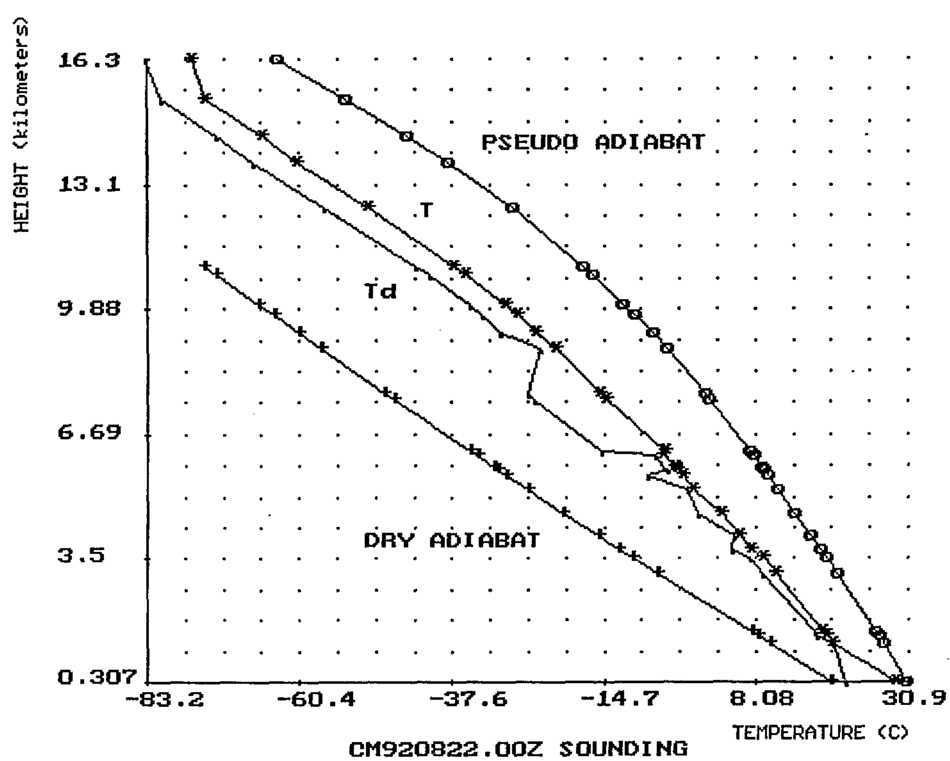

Figure D.3.3. - Atmospheric sounding taken at Chiang Mai, Thailand, August 22, 1992, 0000 GMT.

D.3.2 CCN (Cloud Condensation Nuclei) Spectra

No information existed regarding the CCN (cloud condensation nuclei) spectrum for the proposed target area. At first, meteorological and geographical considerations indicated that the nucleus spectrum over the proposed target area was typical of a maritime spectrum that was slightly modified by a short trajectory over land. This nuclei spectrum, referred to as NS #2, was used in phases 1 and 3 of the study. However, observations of frequent haze in the proposed target area resulting from the burning of crop fields and trees indicated that the nucleus spectrum might be more continental than suspected. Warner and Twomey (1967) have shown that the burning of sugar cane fields resulted in significantly higher concentrations of CCN and cloud base droplets than that measured prior to the sugar cane harvesting season. Therefore, 5 nuclei spectra ranging from maritime to continental in character, NS #1 through NS #5 respectively, were used in the phase 2 studies. All of the nuclei spectra were either measured or derived by scientists in other parts of the world. The 5 input nuclei spectra that were used are listed in table D.3.2. Although the various nuclei spectra differ somewhat in the breadth of the nuclei distribution (fig. D.3.4), the most significant difference is in the number of nuclei activated at cloud base (table D.3.2 and fig. D.3.5).

Table D.3.2.- Nuclei spectra used in the model calculations.

Nuclei Spectra Number	CCN Concentration (#/cm^3)	Source
NS #1	184	Ocean off Florida, U.S.
NS #2	308	Florida, U.S. (land)
NS #3	364	Bemidji, MN, U.S.
NS #4	729	NS #3 times 2
NS #5	855	Continental U.S.

D.3.3 Hygroscopic Seeding Chemicals

The model seeding experiments focused mainly on the use of four hygroscopic chemicals: sodium chloride, calcium chloride, ammonium nitrate, and urea. These chemicals were selected for study because they were the principal chemicals being used in Thailand's operational warm cloud seeding program. Of these four chemicals, calcium chloride is exothermic and the rest are endothermic. Table D.3.3 gives the physical-chemical properties of these chemicals.

Table D.3.3. - Physical-chemical properties of hygroscopic chemicals.

Physical-Chemical Property	Calcium Chloride	Sodium Chloride	Ammonium Nitrate	Urea
Mol. Wt. (g)	111.01	58.45	50.05	60.06
Solubility (g/g)	0.745	0.360	1.183	0.850
Heat of Dissolution (kcal/g-mole)	-19.823	+0.928	+6.140	+3.334
Activation rel hum (%)	18	75	67	81
Density Sat. Solution (g/cm^3)	1.4258	1.2023	1.246	1.130
Density (g/cm^3)	2.150	2.165	1.660	1.335
No. of Particles/No. of H_2O Drops	0.465	0.462	0.602	0.749

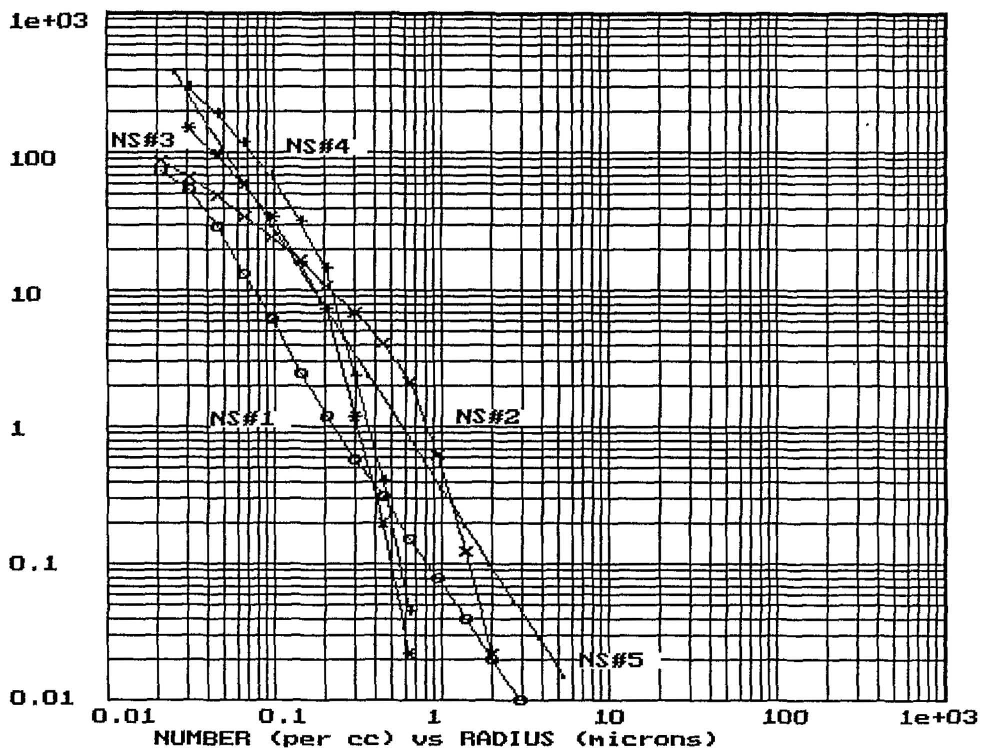

Figure D.3.4. - Model input nuclei spectra.

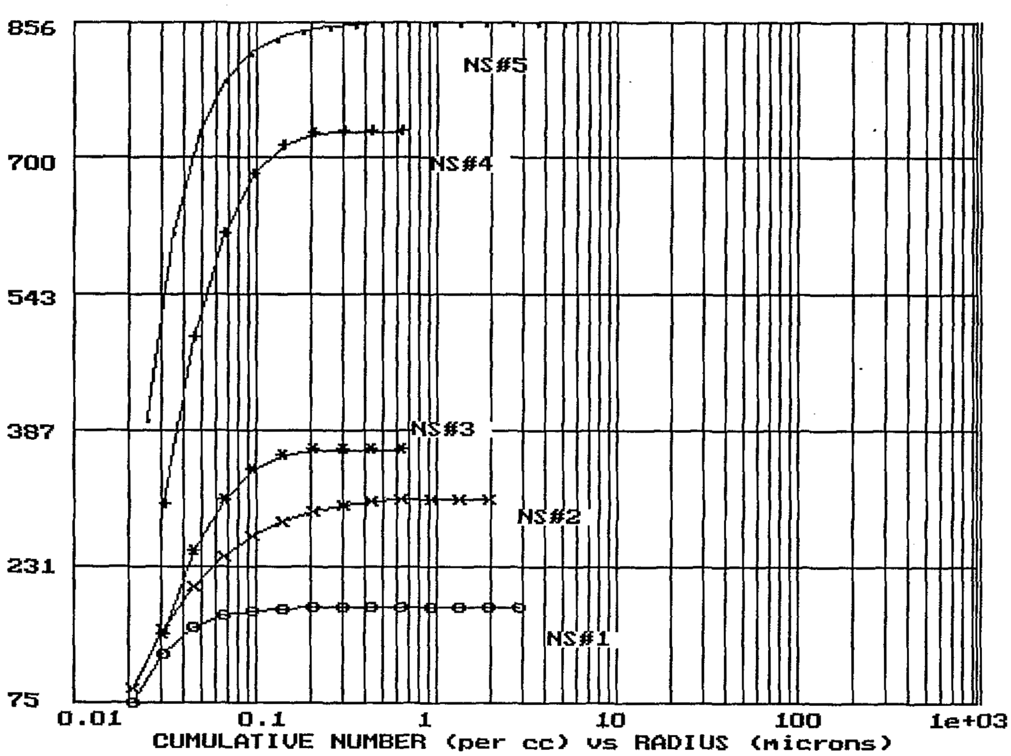

Figure D.3.5. - Cumulative number concentration of model input nuclei.

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The calcium chloride, as purchased, is provided by the manufacturer as a sized powder in 25-kilogram bags. The calcium chloride is dispensed on the aircraft directly from these bags. The other chemicals are obtained from their manufacturers as coarse granules, which are processed on the ground by a grinder prior to loading on the seeding aircraft. The grinder is only capable of producing particles about 200 micrometers in radius and larger.

Size measurements of the calcium chloride were made just after receipt from the manufacturer [referred to as spectra *S*(*mfc*)], and just prior to seeding as the bags were opened on the seeding aircraft, referred to as spectra *S*(*smp*). These size distributions are shown in table D.3.4. The size distribution of the calcium chloride in *S*(*mfc*) is quite broad and degrades to larger sizes during storage to yield *S*(*smp*).

Table D.3.4. - Calcium chloride seeding particle spectra.

Particle Radius (μm)	Percent of Total Mass in Each Size Category	
	S(*mfc*)	*S*(*smp*)
44	27.0	0.8
76	6.0	6.6
151	44.0	61.1
350	23.0	31.5

Hygroscopic end burning flares, as used in South Africa (Mather and Terblanche, 1992), were also tested in the seeding experiments. The hygroscopic chemicals in these flares consist of 21 percent sodium chloride, 67 percent potassium chloride, and 12 percent magnesium oxide. The flares contain about 1 kilogram of hygroscopic chemicals, which burn for about 4 minutes. The particle output of the flares was found by measurement to be distributed log-normally with about 10**11 particles greater than 1 micrometer in diameter. For the purposes of these calculations, the flares were assumed to consist of potassium chloride only.

D.3.4 Seeding Mode

The seeding mode for all chemicals except the hygroscopic flares was to dispense, in a specified time, a specified quantity of seeding chemical out of an aircraft flying at a specified airspeed at a specified level in the cloud. The seeding concentration or *DOSE* (dosage) was defined by these parameters using the assumption that the seeding particles are distributed by the wing tip vortices of the aircraft, in which the *CSA* (cross-sectional area) of the seeded plume is defined as:

$$CSA = 1.75 * WSP ** 2,$$

where *CSA* is in meters squared and *WSP* is the wing span of the aircraft in meters.

The seeding volume (*SVOL*) is then given by:

$$SVOL = CSA * STIME * ASPD * 30.888,$$

where *SVOL* is in cubic meters, *STIME* is the seed time in minutes, *ASPD* is the aircraft speed in knots, and 30.888 is the unit conversion factor.

The seeding concentration or dosage is then given by:

$$DOSE(I) = (TMASS(I) \,/\, SMASS(I)) \,/\, SVOL, I{=}1,.., N$$

where $DOSE(I)$ is the number per cubic meter of seed particles in size class I, $TMASS(I)$ is the total mass in grams of seed particles in size class I that are dispensed, and $SMASS(I)$ is mass in grams of each seed particle in size class I.

Various combinations of aircraft (either a C-47 or CASA aircraft), seeding times (from 8 to 15 minutes), and seeding amounts (*TMASS* from 1000 to 2666 kilograms) were used in these calculations. Using a constant aircraft speed of 120 knots resulted in a range of seeding concentrations or dosages from 0.020555 to 0.061162 gram per cubic meter.

The seeding mode for the hygroscopic flares was quite different. Seeding with the flares was carried out in the subcloud layer by a Cessna 180 aircraft flying at 100 knots and burning 4 flares for 4 minutes. The resulting potassium chloride particles were initially distributed in the volume created by the wing tip vortices, as above, and then spread farther by turbulence for about 1 hour using turbulent parameters typical of small cumulus conditions (World Meteorological Organization, 1980). The resulting concentration of potassium chloride particles was then added to the natural nuclei spectra (NS #1, NS #2, etc.) to yield mixed nuclei spectra (NSFL #1, NSFL #2, etc.). The initial flare particle size distribution and that after 60 minutes dispersion is shown on figure D.3.6. The flare particle size spectra after 60 minutes dispersion under cumulus conditions is also shown on figures D.3.4 and D.3.5. The number activated at cloud base was determined by the maximum supersaturation of air having a temperature and updraft consistent with that at cloud base. The net result was to make natural nuclei spectra that were continental in character more maritime in character, and leave natural nuclei spectra that were similar to the flare spectra basically unchanged (figs. D.3.7.a, D.3.7.b, and D.3.7.c).

D.4 Physical-Chemical Properties of the Hygroscopic Agents

Before presenting the results of the seeding experiments, the physical-chemical properties of the various hygroscopic seeding chemicals will be examined to see if they provide a clue to their relative effectiveness. Hygroscopicity is generally defined as the ability of a chemical to accelerate the condensation of water vapor, or some measure of this ability (American Meteorological Society, 1959). The usual measure of hygroscopicity is the relative humidity at which the chemical begins to condense water. The four hygroscopic chemicals considered here thus rank in the order 1) calcium chloride, 2) ammonium nitrate, 3) sodium chloride, and 4) urea, which begin to condense water at 18 percent, 67 percent, 75 percent, and 81 percent relative humidity, respectively (see table D.3.3).

Low (1969), on the other hand, proposed a definition which he believes is more appropriate for weather modification. He defines weather modification hygroscopicity as the mass of hygroscopic chemical in 1 kilogram of pure water that is required to achieve a given degree of vapor pressure lowering, for example, 0.95. By this definition, the four hygroscopic chemicals rank in the order 1) sodium chloride, 2) calcium chloride, 3) ammonium nitrate, and 4) urea. Low's ranking of chemicals by weather modification hygroscopicity is different than the ranking under the conventional definition of hygroscopicity. Both rankings are apparent on figure D.4.1, which gives the equilibrium saturation ratio of 5-micrometer hygroscopic particles growing at a temperature of 20 °C, pressure of 900 millibars, and relative humidity of 100 percent.

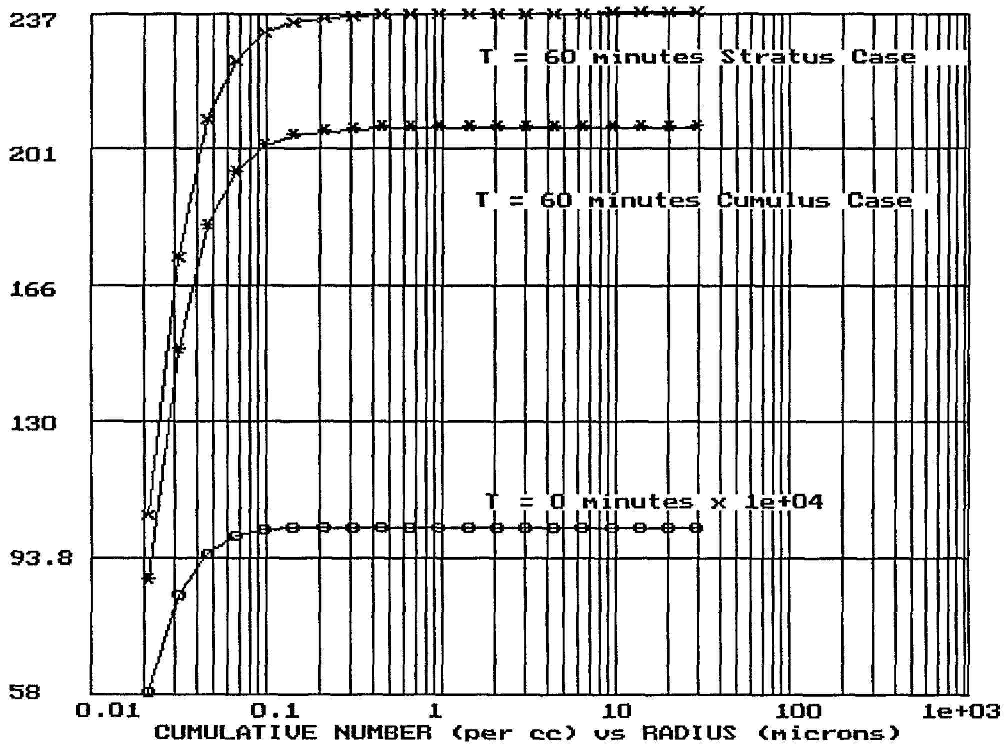

Figure D.3.6. - Cumulative number concentration of the hygroscopic flare nuclei as released and after 60 minutes dispersion under stratus and cumulus conditions.

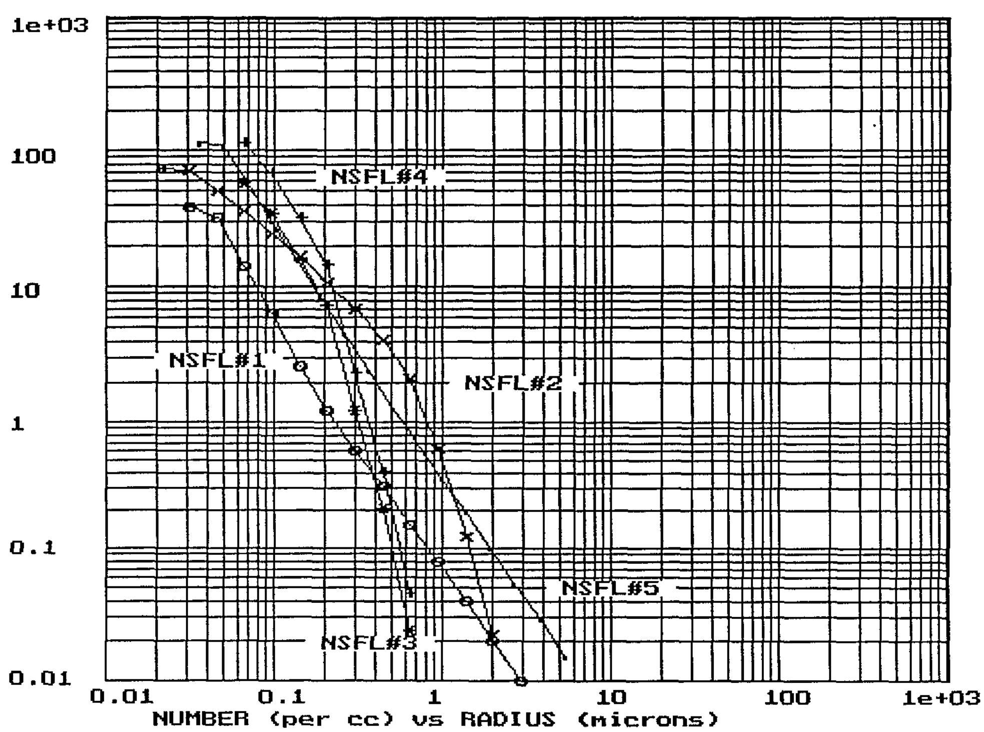

Figure D.3.7.a. - Spectra of combined natural nuclei and hygroscopic flare nuclei activated under typical cloud conditions.

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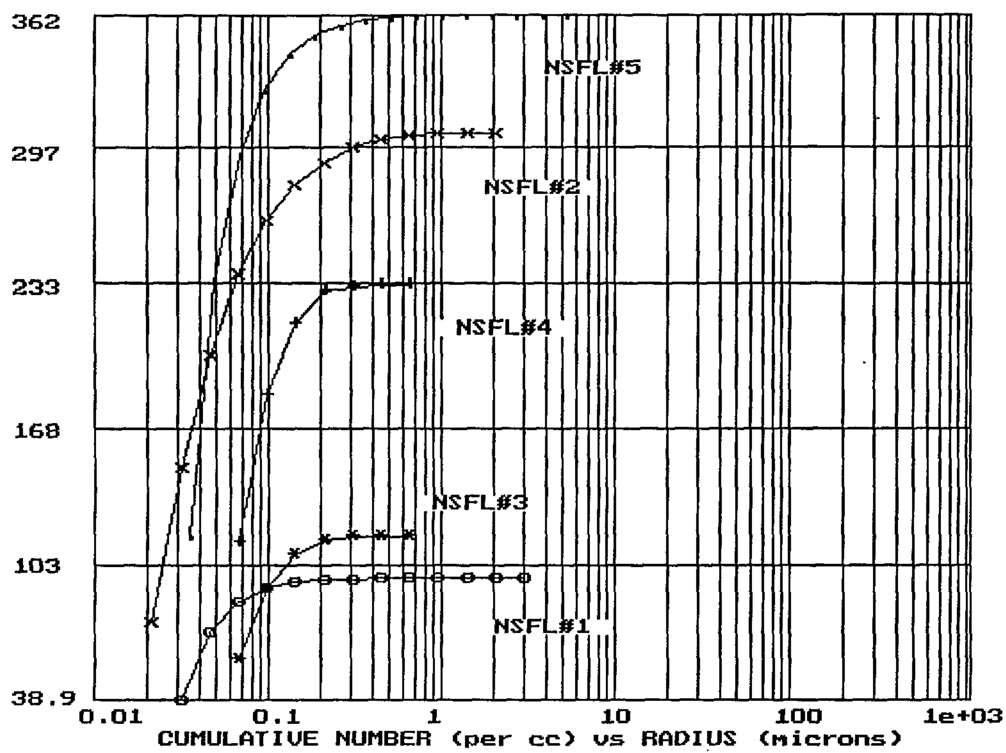

Figure D.3.7.b. - Cumulative number concentration of combined natural nuclei and hygroscopic flare nuclei activated under typical cloud conditions.

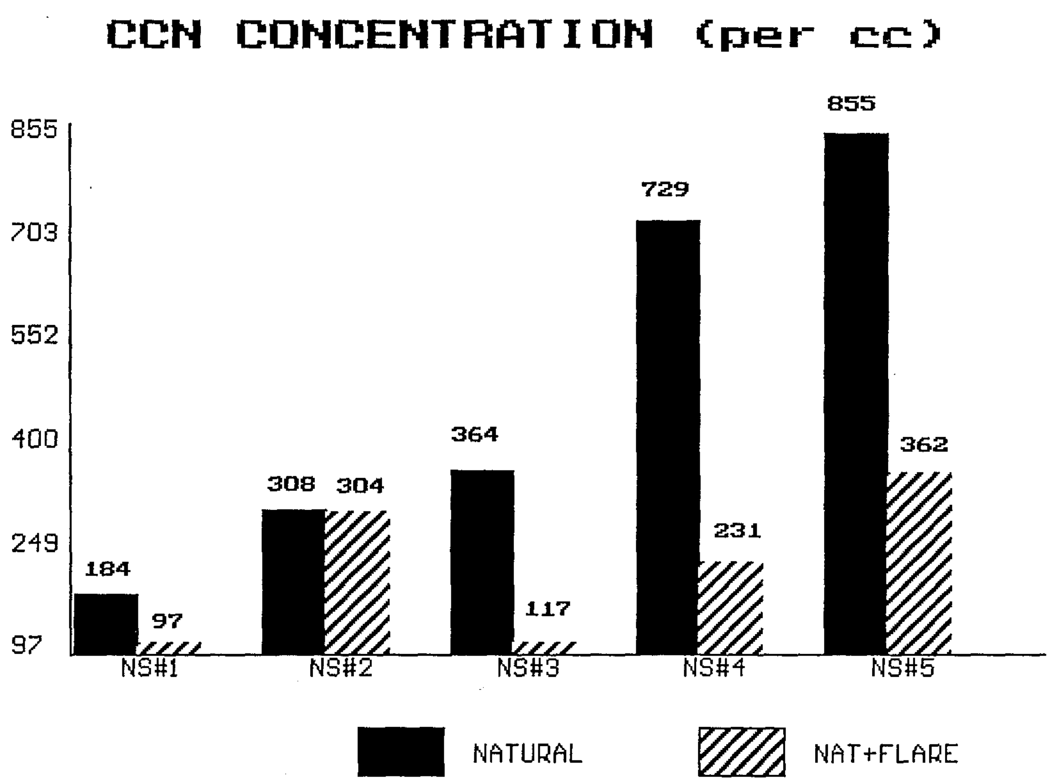

Figure D.3.7.c. - Comparison between CCN activated at cloud base for natural nuclei spectra (NS #1 . . . NS #5) and natural nuclei spectra modified by the hygroscopic flares (NSFL #1 . . . NSFL #5).

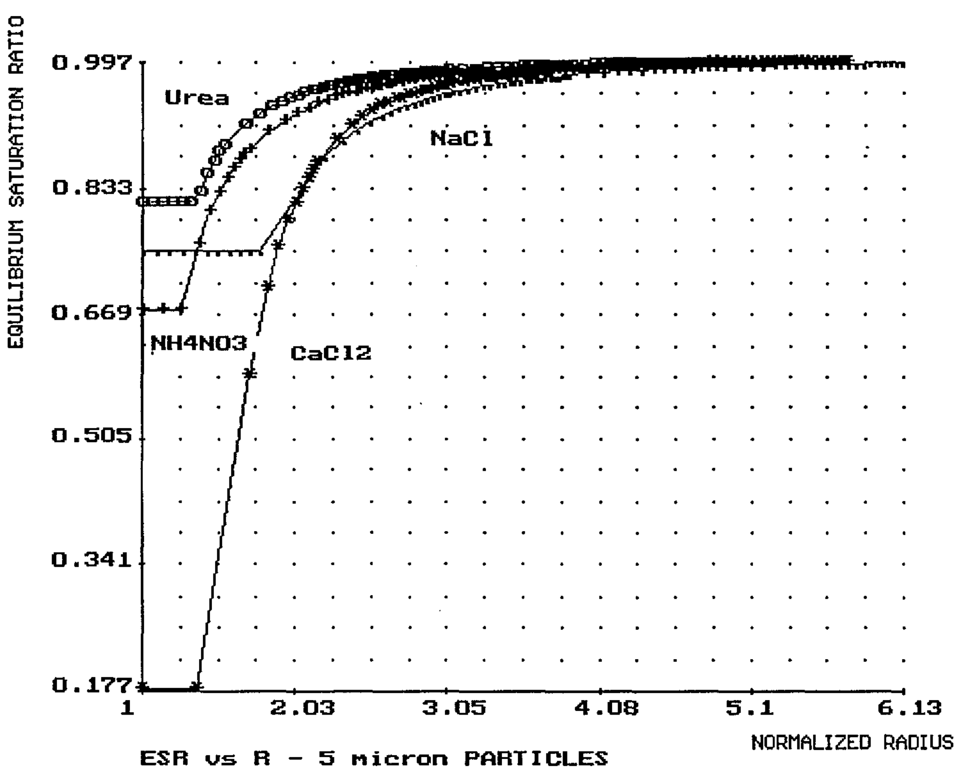

Figure D.4.1. - Equilibrium saturation ratio as a function of normalized radius, *R*(*t*)/*R*(0), for four hygroscopic chemicals.

In considering a definition for weather modification hygroscopicity, practical considerations such as economically achievable seeding particle sizes and cloud time available for action must be taken into account. In real warm cloud seeding experiments, seeding particle sizes from 10 to several hundred micrometers in radius are common, and the time available tends to be short. In addition, the time during which condensation exerts a major influence occurs for a very short time after introduction, after which time coalescence dominates and the seed particles become dilute solutions very rapidly.

Figures D.4.2.a, D.4.2.b, and D.4.2.c present the results of growing 10-, 30-, and 50-micrometer radius hygroscopic particles for 300 seconds in the same environment as prescribed for figure D.3.8. These figures show that the time required for the growth of the sodium chloride to overtake the growth of the ammonium nitrate particles and calcium chloride particles increases with increasing particle size. The growth of the sodium chloride particles overtakes that of the ammonium chloride relatively quickly, but quite a bit of time is required for the growth of the sodium chloride particles to overtake the growth of the calcium chloride particles, even though the vapor pressure lowering capability of the sodium chloride is better than calcium chloride. If this criterion is used as a definition of practical weather modification hygroscopicity, the rank order of the four hygroscopic chemicals becomes 1) calcium chloride, 2) sodium chloride, 3) ammonium nitrate, and 4) urea. This one criterion, of course, is not the whole story. In a fixed seeding payload, as constrained by the aircraft, the relative density of the hygroscopic chemicals must be considered because it determines the number of seeding particles injected into the cloud. The density of calcium chloride is roughly equal to that of sodium chloride, but the densities of ammonium nitrate and urea are quite a bit smaller (see table D.3.3). Thus, for a given payload of seeding material and given seeding particle size, more particles of ammonium nitrate and urea will be injected into the cloud than that of calcium chloride and sodium chloride, and this factor could change the rank order of effectiveness of the hygroscopic chemicals.

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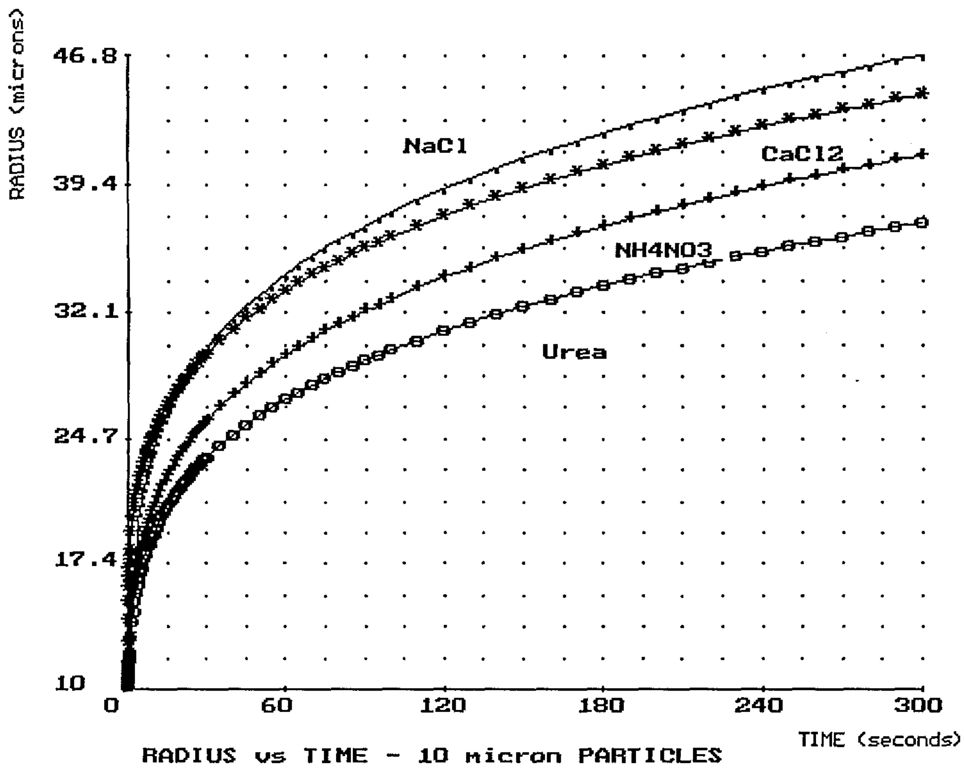

Figure D.4.2.a. - Radius of 10-micron-radius hygroscopic particles as a function of time.

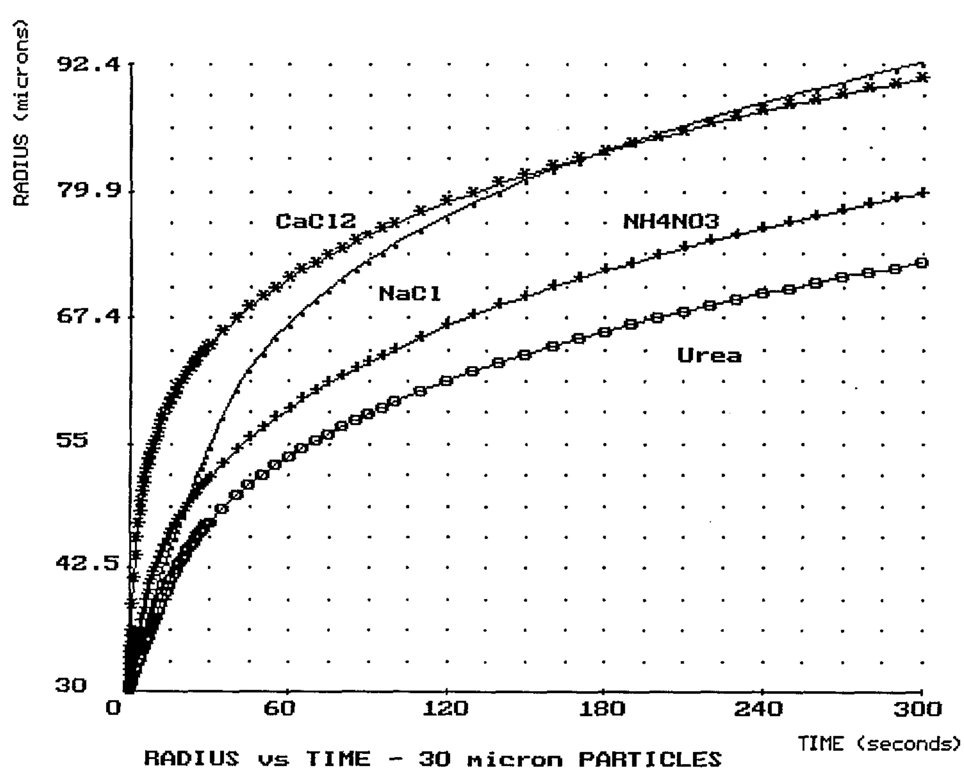

Figure D.4.2.b. - Same as figure D.4.2.a but for 30-micron-radius hygroscopic particles.

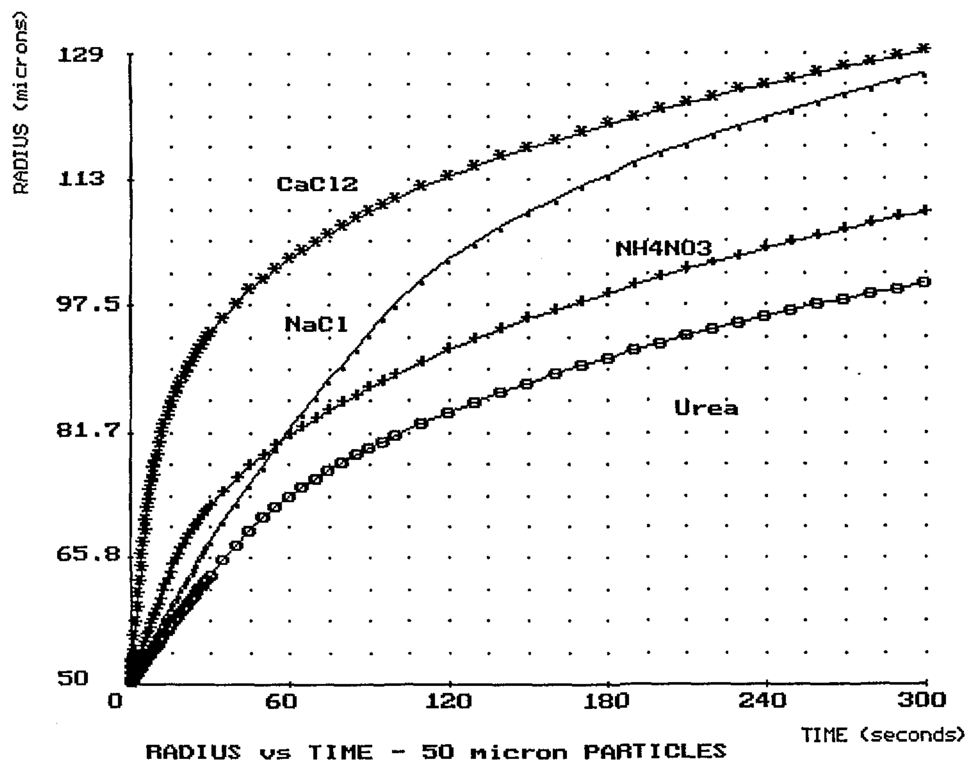

Figure D.4.2.c. - Same as figure D.4.2.a but for 50-micron-radius hygroscopic particles.

What is the effect of the exothermic/endothermic property of various hygroscopic chemicals? For a given payload, the change in temperature produced by the heat released/absorbed during the dissolution of the exothermic/endothermic chemicals is independent of seeding particle radius, temperature, pressure, and relative humidity. On the other hand, the change in temperature caused by condensation on the seeding particles varies with all of these parameters. Typical temperature changes caused by dissolution and condensation for the same seeding dosage and environmental parameters but different particle radii are shown in table D.4.1. The temperature change caused by heat of dissolution is inconsequential when compared to the corresponding temperature changes caused by condensation. In view of this finding, seeding with hygroscopic chemicals is not expected to result in dynamic changes in the cloud.

Table D.4.1. - Temperature changes caused by *DTSOL* (heat of dissolution) and *DTCON* (condensation) for hygroscopic particle seeding concentration of 0.020555 gram per cubic meter, temperature of 20 °C, pressure of 900 millibars, and relative humidity of 100 percent.

Particle Radius	*DTSOL* (°C)				*DTCON* (°C)			
(µm)	NaCl	NH_4NO_3	Urea	$CaCl_2$	NaCl	NH_4NO_3	Urea	$CaCl_2$
10	-.0012	-.0060	-.0044	.0140	.836	.689	.614	.776
20	-.0012	-.0060	-.0044	.0140	.373	.293	.275	.394
30	-.0012	-.0060	-.0044	.0140	.219	.176	.163	.275
40	-.0012	-.0060	-.0044	.0140	.130	.121	.109	.215
50	-.0012	-.0060	-.0044	.0140	.075	.090	.076	.177

D.5 Results of the Hygroscopic Seeding Experiments

Given the above background information, the results of the seeding experiments in phases 1, 2, and 3 are presented. The results are quite clear and essentially speak for themselves.

D.5.1 Phase 1 Experiments

D.5.1.1 Sensitivity to hygroscopic chemical type

Figures D.5.1.a and D.5.1.b show the relative effectiveness of seeding with 10-micrometer-radius particles of the 4 hygroscopic chemicals at a seeding concentration of 0.05353 gram per cubic meter. Results are given for seeding at cloud base and 200 meters below cloud top 5 minutes after the cloud initially develops, at which time the cloud depth was 1200 meters. Figure D.5.1.b gives the results in the form of $S(H)/S(W)$ to isolate the effect of hygroscopicity. It should be noted that seeding with this concentration of water drops would produce 0.011 millimeter of rain on the ground if all the water drops fell to the ground without growing, detraining, or evaporating. It should also be noted that seeding with 10-micrometer-radius water drops at cloud base and near cloud top did not result in any more rain than the natural cloud produced. Consistent with the discussion in section D.4., the effectiveness ranking is 1) sodium chloride, 2) calcium chloride, 3) ammonium nitrate, and 4) urea for both cloud base and cloud top seeding.

Similar calculations were also done for 50-micrometer-radius seeding particles. In this case, the water seeding did result in more rain than the natural cloud yielding seed - no seed ratios of 4.0 and 19.8 for cloud top and cloud base seeding, respectively. The seeding results are given on figures D.5.2.a and D.5.2.b. Now the effectiveness ranking changes to 1) calcium chloride, 2) ammonium nitrate, 3) sodium chloride, and 4) urea for both cloud base and cloud top seeding. These results are also consistent with the discussion in section D.4; apparently, the increased number concentration of ammonium nitrate particles rendered those particles more effective than the sodium chloride particles.

The rank orders of hygroscopic chemical effectiveness in accordance with the various definitions mentioned above are summarized in table D.5.1.

Table D.5.1.- Rank orders of the four hygroscopic chemicals.

	Hygroscopicity Definition			
		Cloud Seeding	Practical Cloud Seeding	
Rank	Conventional	(Low)	$R < 15$	$R > 15$
1	$CaCl_2$	NaCl	NaCl	$CaCl_2$
2	NH_4NO_3	$CaCl_2$	$CaCl_2$	NH_4NO_3
3	NaCl	NH_4NO_3	NH_4NO_3	NaCl
4	Urea	Urea	Urea	Urea

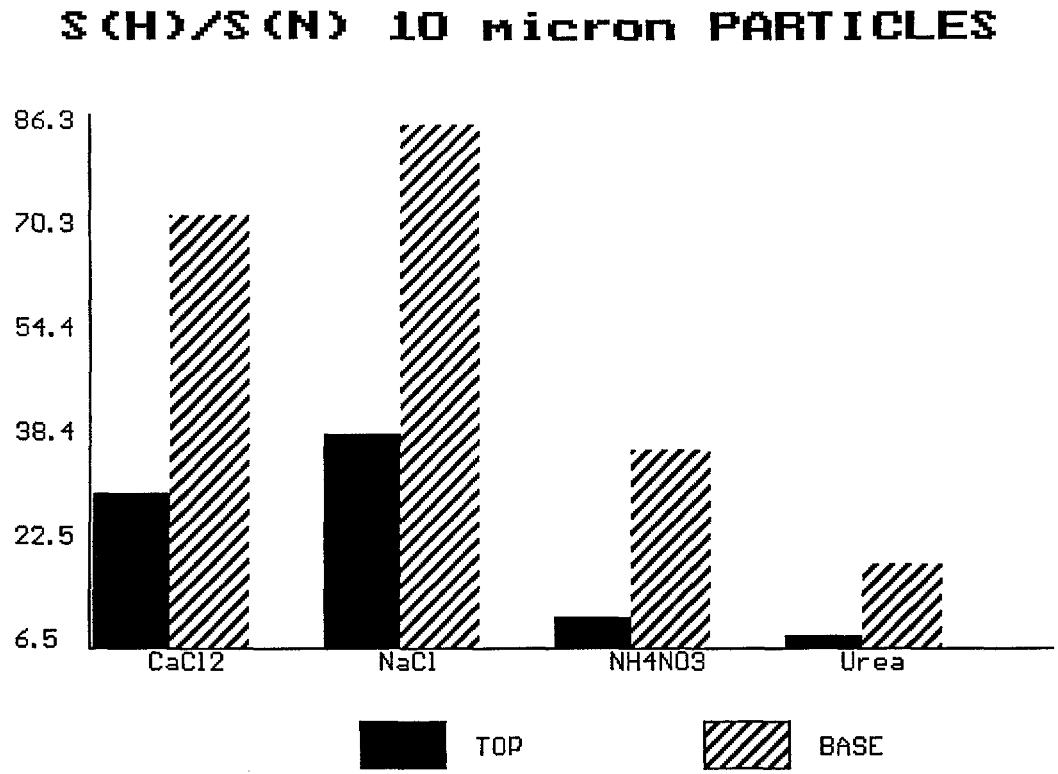

Figure D.5.1.a. - Seed-no seed ratios for hygroscopic particle seeding with 10-micron-radius particles at cloud base and near cloud top 5 minutes after cloud formation.

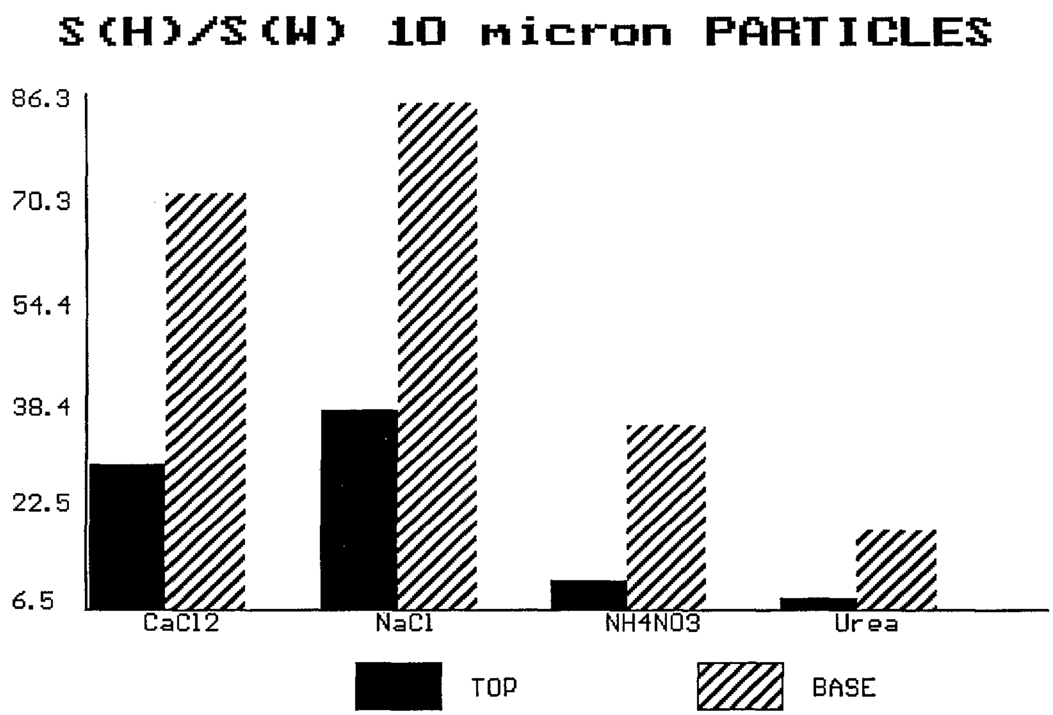

Figure D.5.1.b. - Ratio of hygroscopic to equivalent water particle seeding with 10-micron-radius particles at cloud base and near cloud top 5 minutes after cloud formation.

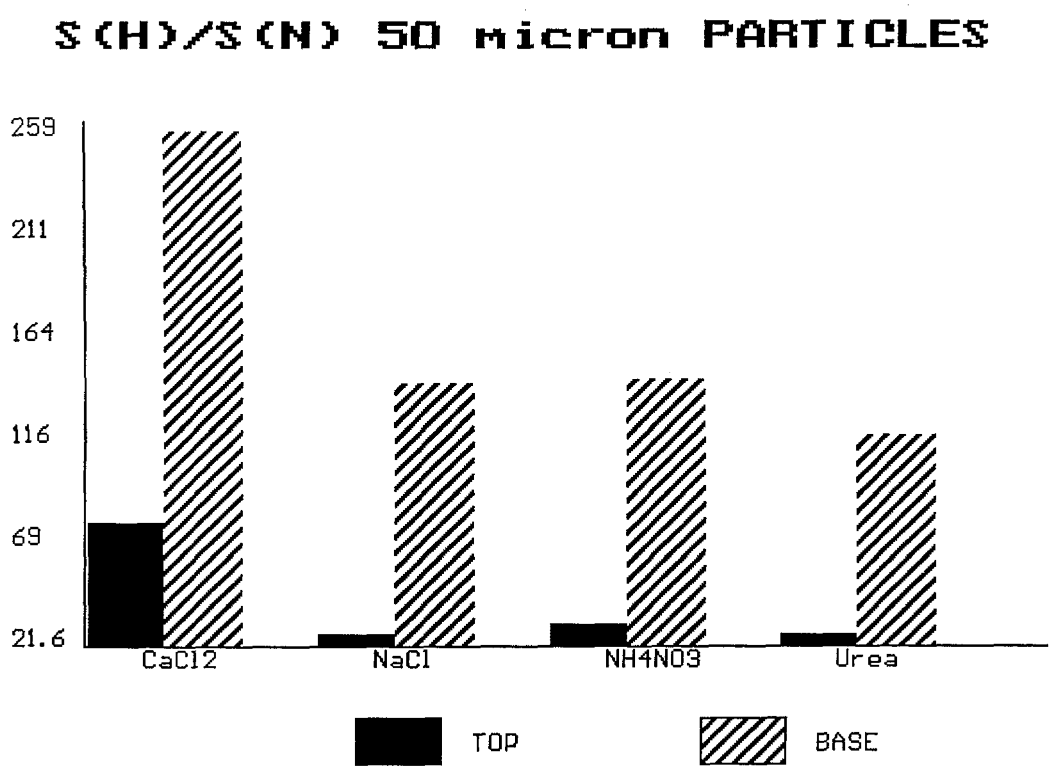

Figure D.5.2.a. - Same as figure D.5.1.a but for 50-micron-radius particles.

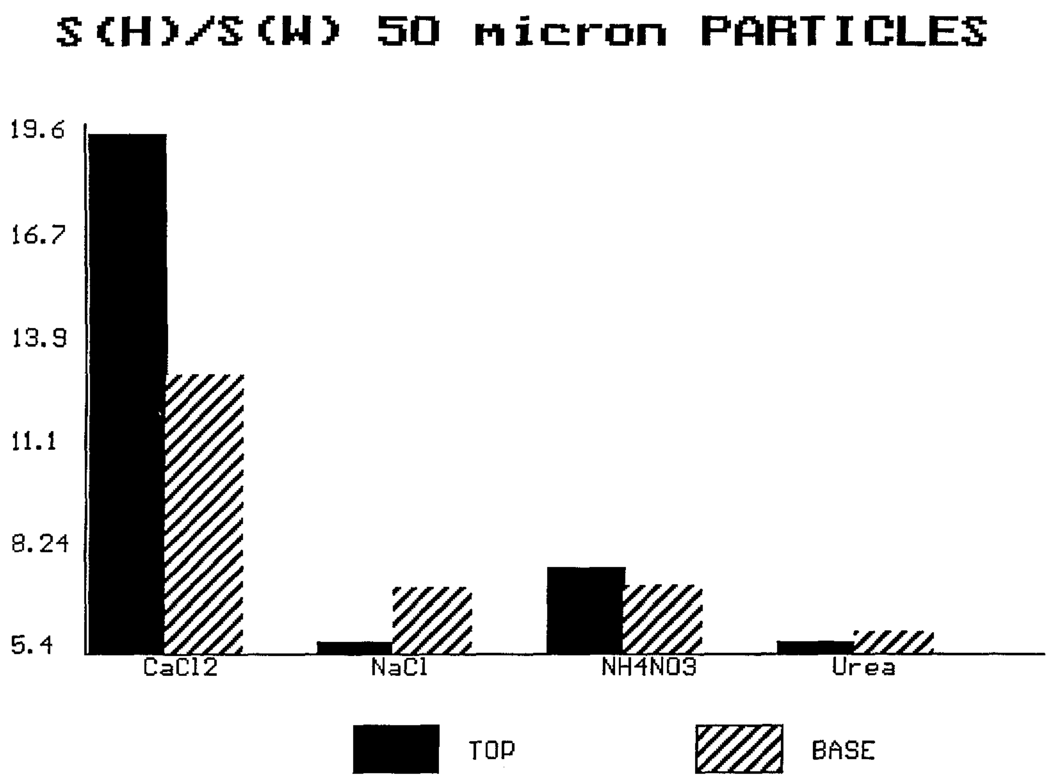

Figure D.5.2.b. - Same as figure D.5.1.b but for 50-micron-radius particles.

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D.5.1.2 Dry particles versus saturated solution drop seeding

Figure D.5.3 shows the relative effectiveness of seeding with 70-micrometer-radius dry and saturated solution particles near cloud top at a seeding concentration of 0.020555 gram per cubic meter. For this case, the equivalent water drop seeding increased the rainfall with respect to the natural cloud by a factor of 3.912. The figure shows that dry particle seeding is more effective than the saturated solution drop seeding for all hygroscopic chemicals tested.

D.5.1.3 Sensitivity to seeding particle radius

At this point it was concluded that seeding with dry calcium chloride particles would be most effective, and calculations were done to determine the optimum size. To this end, model experiments were conducted in which seeding was performed with various sizes of dry calcium chloride particles at cloud base and near cloud top at a seeding concentration of 0.030581 gram per cubic meter. The results of these model runs are given on figure D.5.4. It should be noted that equivalent seeding with water drops produced seed-no seed ratios of 1.0 for 10- and 20-micrometer-radius drops and increased thereafter with increasing water drop size to values of 51.04 and 11.5 for cloud base and near cloud top seeding, respectively. It can be seen that for both cloud base and near cloud top seeding, the seed-no seed ratio peaks for 50-micrometer-radius seeding particles. An examination of the ratios of calcium chloride to water drop seeding reveals that they peak at a 20-micrometer-radius for cloud base seeding and at a 30-micrometer-radius for near cloud top seeding. Figure D.5.4 also shows that seeding with the calcium chloride spectra produces substantial results; the *S*(*mfc*) spectra produced results 67 percent and 55 percent of the 50-micrometer peak value for near cloud top and cloud base seeding, respectively, and the *S*(*smp*) produced results 44 percent and 35 percent of the peak value for near cloud top and cloud base seeding, respectively.

Suspecting that the results of such calculations might differ for clouds in which water loading was not a constraint, similar seeding experiments were conducted on a natural cloud that developed in the absence of water loading. By deactivating the water loading term, the cloud is effectively growing in a wind shear environment in which the rain falls outside of the main updraft. Table D.5.2 compares the natural clouds that developed with and without water loading. With water loading deactivated, the cloud is deeper, lasts longer, and produces considerably more rain. Figure D.5.5 gives the results of the model seeding experiments.

Table D.5.2.- Comparison of natural cloud characteristics for the cloud with and without water loading.

Cloud Characteristic	With Water Loading	Without Water Loading
Cloud Base Temp (°C)	20	20
Cloud Depth (m)	2200	4200
Cloud Duration (min)	33	54
Rain Efficiency (%)	0.043	7.575
Rain on Ground (mm)	0.0024	1.1226
Updraft Maximum (m/s)	6.07	6.15
First Rain in Cloud (min)	12	11
First Rain on Ground (min)	20	20

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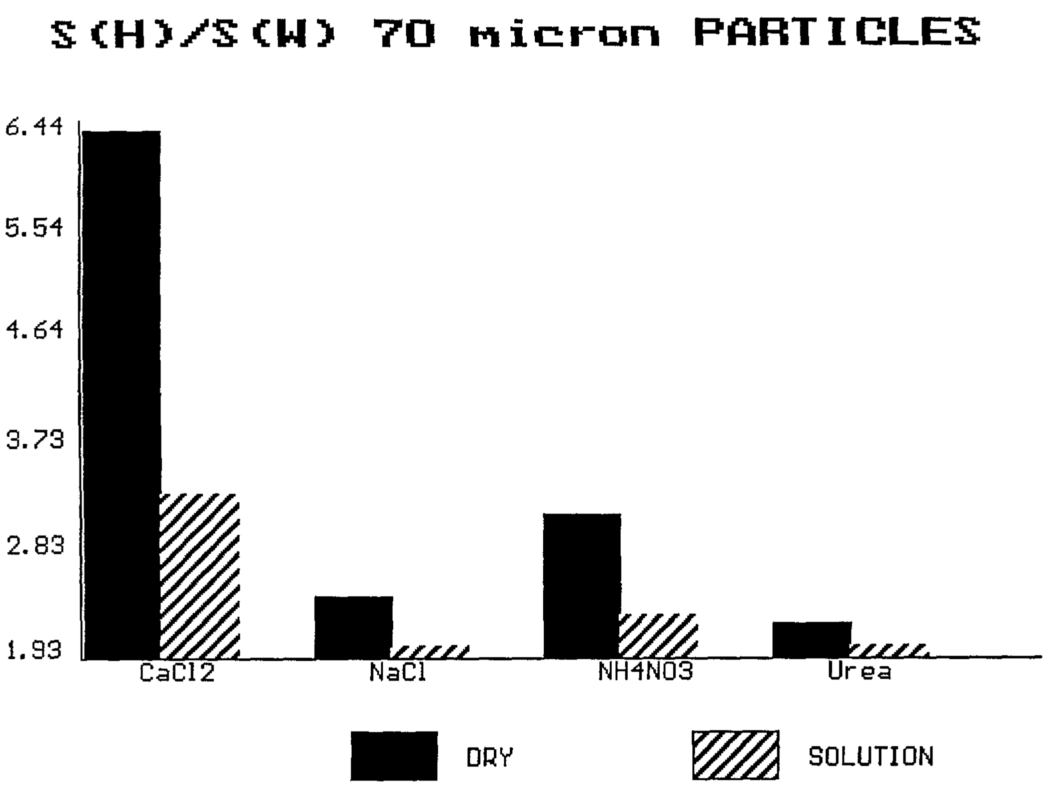

Figure D.5.3. - Ratio of hygroscopic to equivalent water particle seeding with 70-micron-radius dry and saturated solution particles near cloud top 5 minutes after cloud formation.

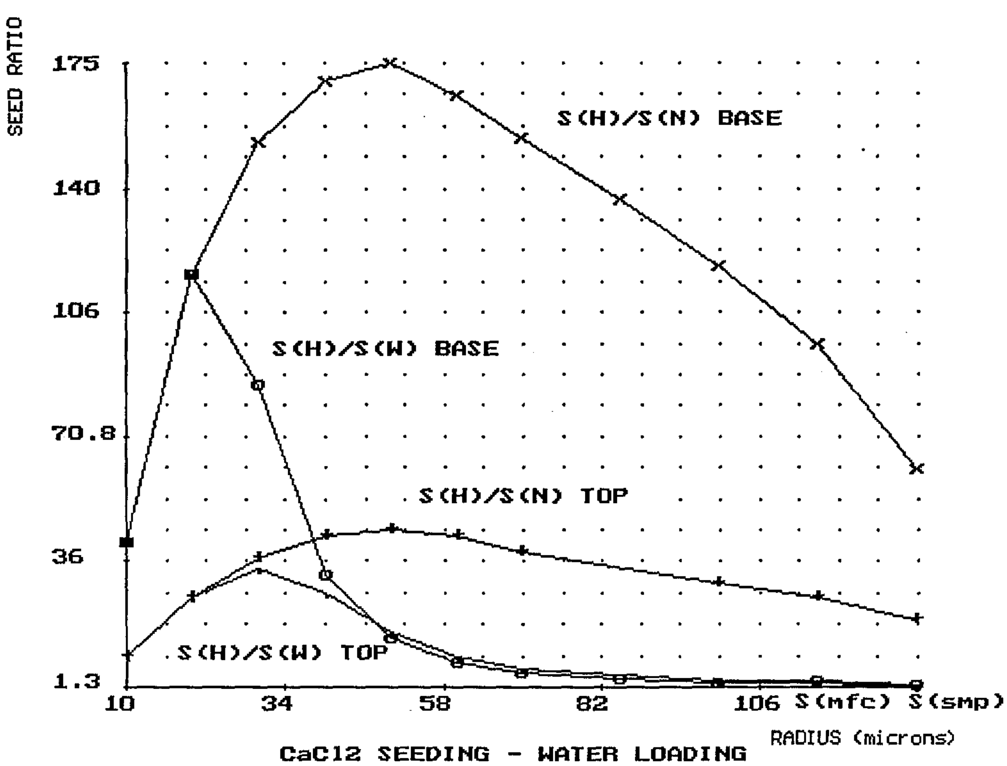

Figure D.5.4. - Relative effectiveness of calcium chloride particle seeding as a function of seeding particle size in a cloud in which water loading is active.

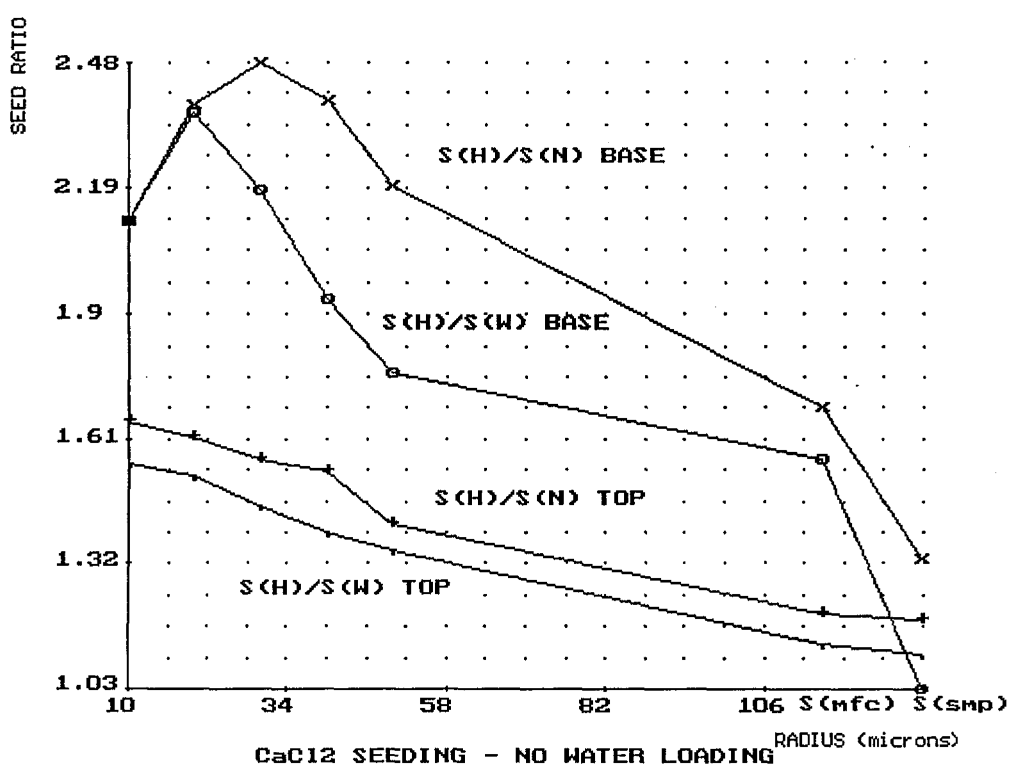

Figure D.5.5. - Relative effectiveness of calcium chloride particle seeding as a function of seeding particle size in a cloud in which water loading is not active.

Figure D.5.5 shows that the results of seeding the cloud without water loading are dramatically different from the results of seeding the cloud with water loading as given on figure D.5.4. One notable difference is that all of the seed-no seed ratios are substantially smaller for the no water loading cloud. An apparent upper limit exists to how much the precipitation efficiency can be improved, and the precipitation efficiency of the natural cloud with no water loading seems to be closer to that limit than the cloud without water loading. It can also be seen that the seed-no seed ratio in this case peaks at a 30-micrometer-radius for cloud base seeding and at 10 micrometers or less for near cloud top seeding. An examination of the ratios of calcium chloride to water drop seeding reveals that they peak at a 20-micrometer-radius for cloud base seeding and at a 10-micrometer-radius or less for near cloud top seeding. Figure D.5.5 also shows that seeding with the calcium chloride spectra produce meaningful results; the *S*(*mfc*) spectra produced results 73 percent and 68 percent of the peak value for near cloud top and cloud base seeding, respectively, and the *S*(*smp*) produced results 72 percent and 54 percent of the peak value for near cloud top and cloud base seeding, respectively.

D.5.1.4 Effect of seeding rate

Table D.5.3 illustrates the effect of 50-micrometer-radius calcium chloride seeding at cloud base and near cloud top using various seeding concentrations. Table D.5.3 shows that the seeding effect increases with increasing seeding concentration, which is consistent with the seeding hypothesis that the seed particles are acting as precipitation embryos. Looking at the ratios of calcium chloride to water drop seeding, for near cloud top seeding the ratios increase with seeding concentration, but for cloud base seeding the ratios decrease with

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increasing seeding concentration. It is also interesting to note that seeding with a given concentration of seeding particles produces a much larger effect than two seedings with half that concentration (total concentration is the same) spaced 5 minutes apart.

Table D.5.3. - Relative effects of seeding with 50-micrometer-radius calcium chloride particles at cloud base and near cloud top as a function of seeding concentration.

Seeding Concentration (g/m^3)	Seeding At: Cloud Base (A)	Cloud Base (B)	Near Cloud Top (A)	Near Cloud Top (B)
0.020555	120.0	16.6	27.6	14.1
0.030581	175.0	14.5	44.7	16.5
0.053530	258.7	13.1	78.3	19.6
0.061162	284.0	12.5	93.5	21.0
0.061162*	193.7	14.5	66.4	24.9

(A) Seed-no seed ratio, $S(H)/S(N)$
(B) Ratio of calcium chloride to water drop seeding, $S(H)/S(W)$
* Two seedings of 0.030581 gram per cubic meter each 5 minutes apart

D.5.1.5 Effect of seeding location

An examination of seeding results presented on figures D.5.1, D.5.2, D.5.4, and D.5.5, and table D.5.3 indicates that seeding at cloud base is more effective than seeding near cloud top.

D.5.1.6 Effect of seeding time

Model runs were made to test the relative effectiveness of seeding at various times after the initiation of the cloud. Calcium chloride seeding near cloud top and at cloud base with 10- and 50-micrometer-radius particles at a seeding concentration of 0.05353 gram per cubic meter was carried out at 5, 10, and 15 minutes after cloud formation. Seeding had its greatest effect when carried out at 5 minutes after cloud formation for all cases, and the seeding effect decreased dramatically when carried out at later times. It is very important to carry out seeding early in the life of a cloud, while it is still growing and the initiation and development of precipitation can still be influenced.

D.5.2 Phase 2 Experiments

D.5.2.1 Effect of the nuclei spectrum

The effect of the nucleus spectrum on warm and cold cloud rain production was tested by making model base runs using the nuclei spectra given on figure D.3.4 and the soundings given on figures D.3.2 and D.3.3. The results of these model runs are given on figure D.5.6. The rain produced in each case has been normalized to the rain produced using NS #1 in order to dramatize the reduction in rainfall that occurs as the nuclei spectrum becomes more and more continental in character.

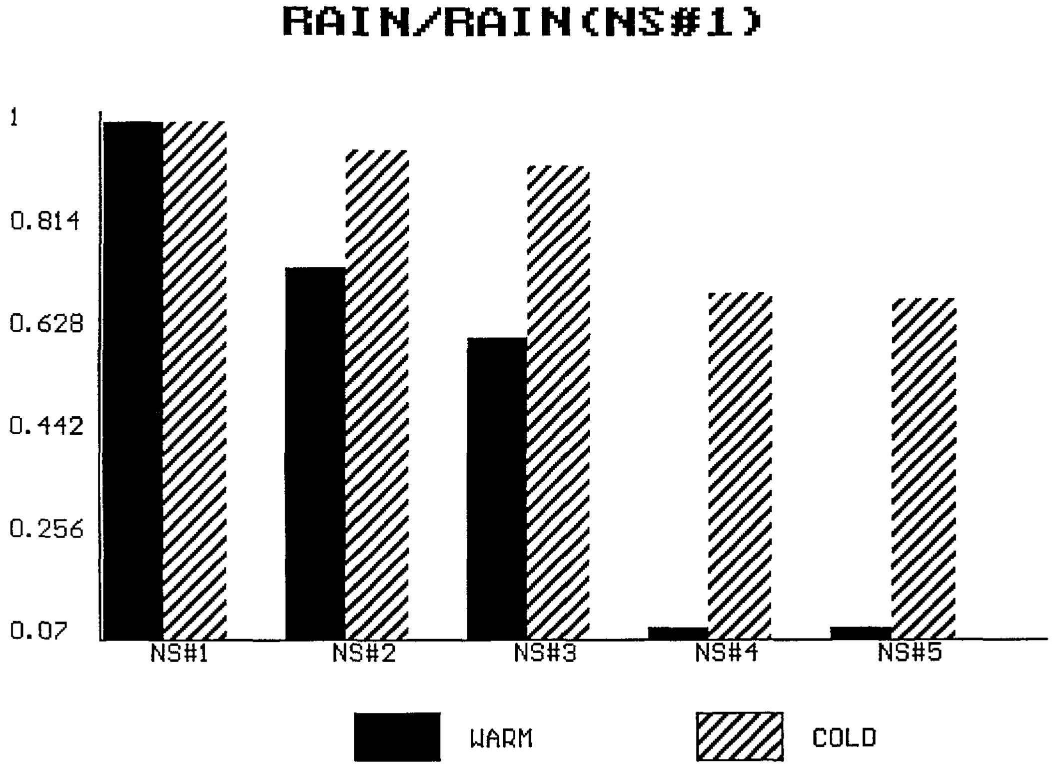

Figure D.5.6. - Model predicted rainfall as a function input nuclei spectra. Rainfall is normalized against the rainfall using NS #1 (MNR).

The natural rainfall produced by using NS #1 can be considered for this study to be the MNR (maximum natural rainfall) for the day. It can be seen that the impact of the nuclei spectrum on rainfall is greatest for the warm clouds, which depend solely on the condensation-coalescence for rain development. Rain development in the cold clouds also include ice processes.

D.5.2.2 Results of seeding

Each of the model base runs (5 warm cloud and 5 cold cloud runs) described above was then subjected to seeding with calcium chloride particle spectra *S(mfc)* and *S(smp)*, as shown in table D.3.3, using a seeding concentration of 0.068519 gram per cubic meter. The seeding was performed 5 minutes after the formation of the cloud, both at cloud base and near cloud top. Each of the base runs was also rerun using the combined nuclei and hygroscopic flare spectra shown on figures D.3.7.a and D.3.7.b to test the effectiveness of the hygroscopic flare seeding. The seed-no seed results of the seeding runs are given on figures D.5.7.a and D.5.7.b for the warm and cold clouds, respectively. An examination of these figures reveals the following results:

1. Calcium chloride seeding results in precipitation increases from cold as well as warm clouds.

2. The calcium chloride seed-no seed ratios for both the warm and cold clouds increase as the natural nuclei spectrum changes from maritime to continental; for the cold clouds, the ratio is greater than for warm clouds for NS #1, NS #2, and NS #3, but the ratio is smaller for NS #4 and NS #5.

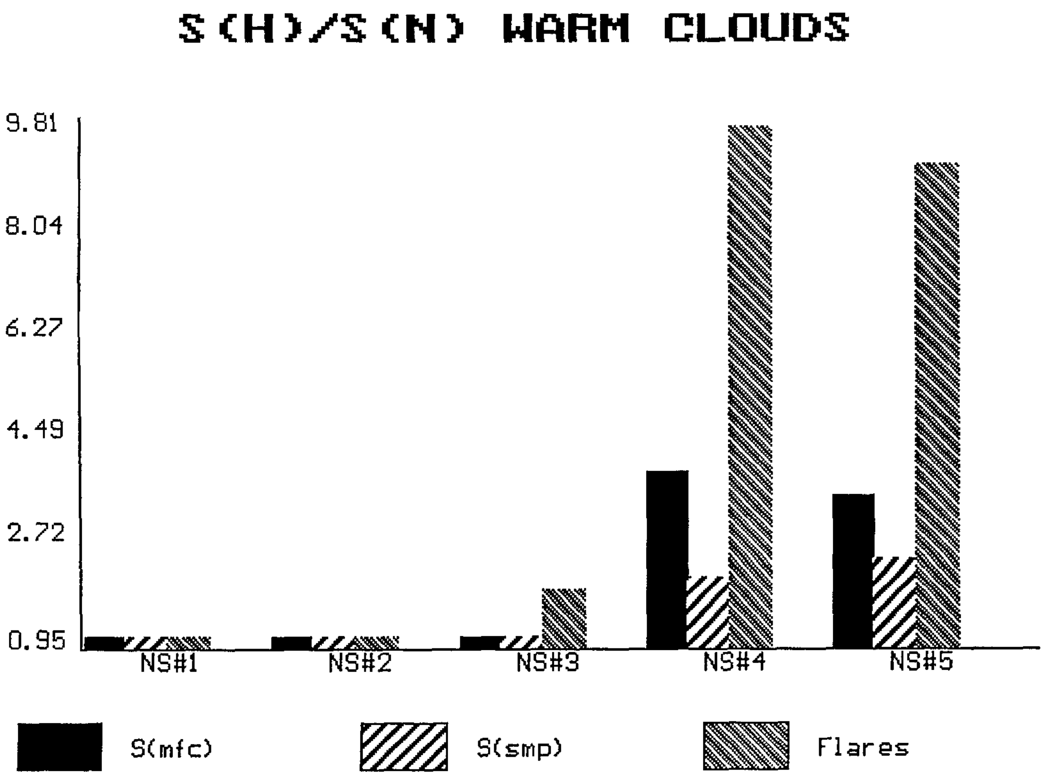

Figure D.5.7.a. - Seed-no seed ratios for warm clouds formed using the five input nuclei spectra when seeded with calcium chloride particle spectra *S(mfc)* and *S(smp)*, and with the hygroscopic flares.

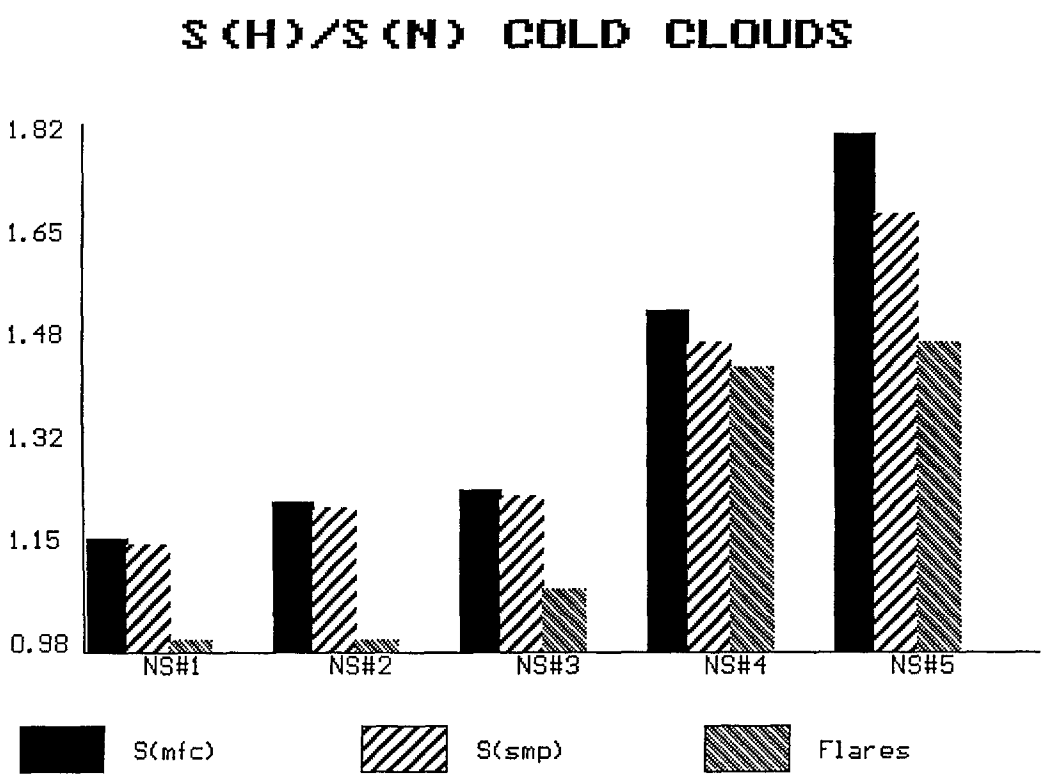

Figure D.5.7.b. - Same as figure D.5.7.a but for cold clouds.

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3. The seed-no seed ratios for calcium chloride seeding with particle spectrum *S*(*mfc*) are always higher than those for the *S*(*smp*) particle spectrum for both warm and cold clouds.

4. Flare seeding does not meaningfully change the CCN concentration of the NS #2 spectrum and, therefore, flare seeding in this case has no effect on rainfall for both warm and cold clouds.

5. Except for NS #2, for which no seeding effect exists, flare seeding produces a significantly greater seed-no seed ratio than the calcium chloride seeding for the warm clouds.

6. For the cold clouds, flare seeding has no effect on NS #1 and NS #2, and the seed-no seed ratios for flare seeding on NS #3, NS #4, and NS #5 are less than those for the calcium chloride seeding.

7. Neither flare nor calcium chloride seeding has any effect on the cloud top attained by the warm clouds. However, for the cold clouds, both the flare and calcium chloride seeding causes the cloud top heights to be from 200 to 800 meters lower than the no seed cloud top heights. Improvement of the precipitation efficiency through seeding causes the water loading to limit the growth of the clouds.

The results of these seeding runs are also given on figures D.5.8.a and D.5.8.b for warm and cold clouds, respectively, but the seeded rain has been normalized to the MNR as on figure D.5.6. This normalization was done to see if and by how much seeding can restore the rainfall for the NS #2 to NS #5 cases to the value obtained with a relatively pristine NS #1 maritime nuclei spectrum. It can be seen that the calcium chloride seeding of the cold clouds does, in fact, result in the production of more rain than the MNR in all cases. For the warm clouds, calcium chloride seeding of the NS #2 to NS #5 cases never results in more rain than the MNR, even though the seed-no seed ratios are substantially greater than one. Flare seeding, on the other hand, never results in more rain than the MNR for the cold clouds. It only exceeds the MNR for warm clouds for the NS #1 and NS #3 cases because the flare seeding of the NS #1 and NS #3 cases results in a lower CCN concentration than the no seed NS #1 case.

D.5.3 Phase 3 Experiments

To obtain an estimate of the range of seeding results as a function of atmospheric sounding, seeding was performed on the soundings given in table D.3.1 using the calcium chloride *S*(*mfc*) and *S*(*smp*) seeding spectra. The seeding was carried out 5 minutes after cloud formation near cloud top at a seeding concentration of 0.068519 gram per cubic meter. The results of warm and cold cloud seeding are given in tables D.5.4 and D.5.5, respectively.

Tables D.5.4 and D.5.5 show that the seeding produces measurable rainfall increases in both the warm and cold clouds. The percentage increases were larger for the warm clouds mainly because they rained less naturally. As discussed before (see the discussion of figs. D.5.4 and D.5.5), the more the cloud produces rain naturally, the smaller the increase in rain caused by seeding. It can also be seen that seeding with the *S*(*mfc*) and *S*(*smp*) spectra produce about the same results. More importantly, the seed-no seed ratios with respect to rain efficiency are about the same as those with respect to rain on the ground for both warm and

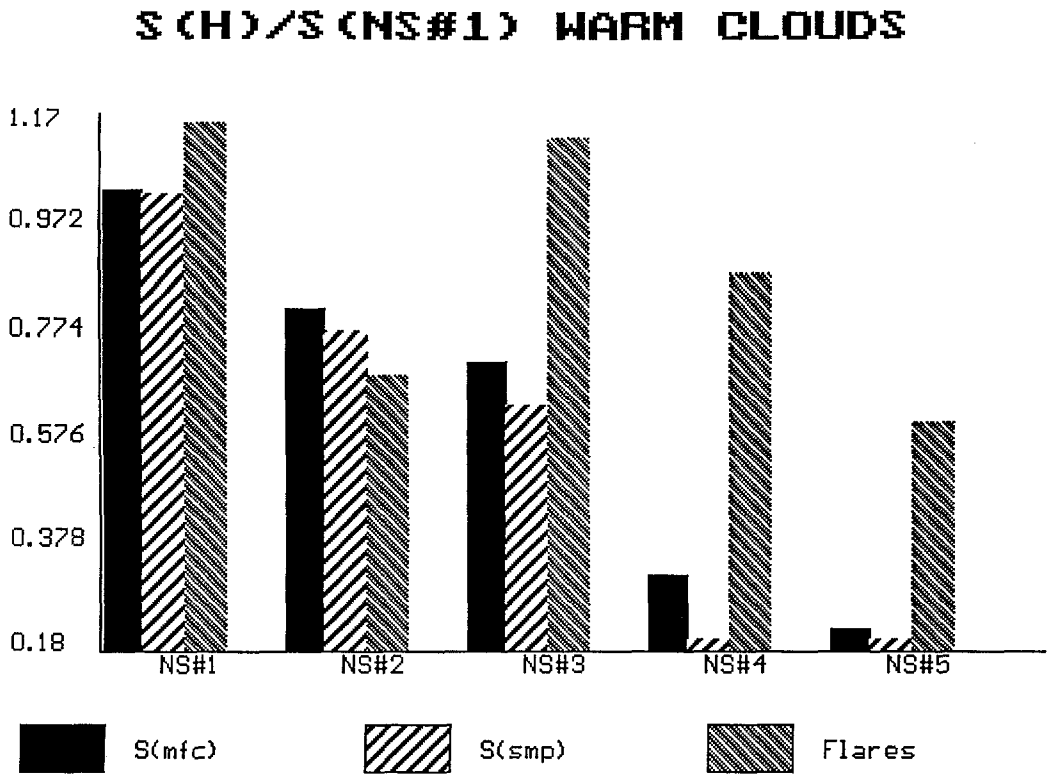

Figure D.5.8.a. - Ratio of seeded rainfall to no seed rainfall using NS #1 (MNR) for warm clouds when seeded with calcium chloride particle spectra *S*(*mfc*) and *S*(*smp*), and with the hygroscopic flares.

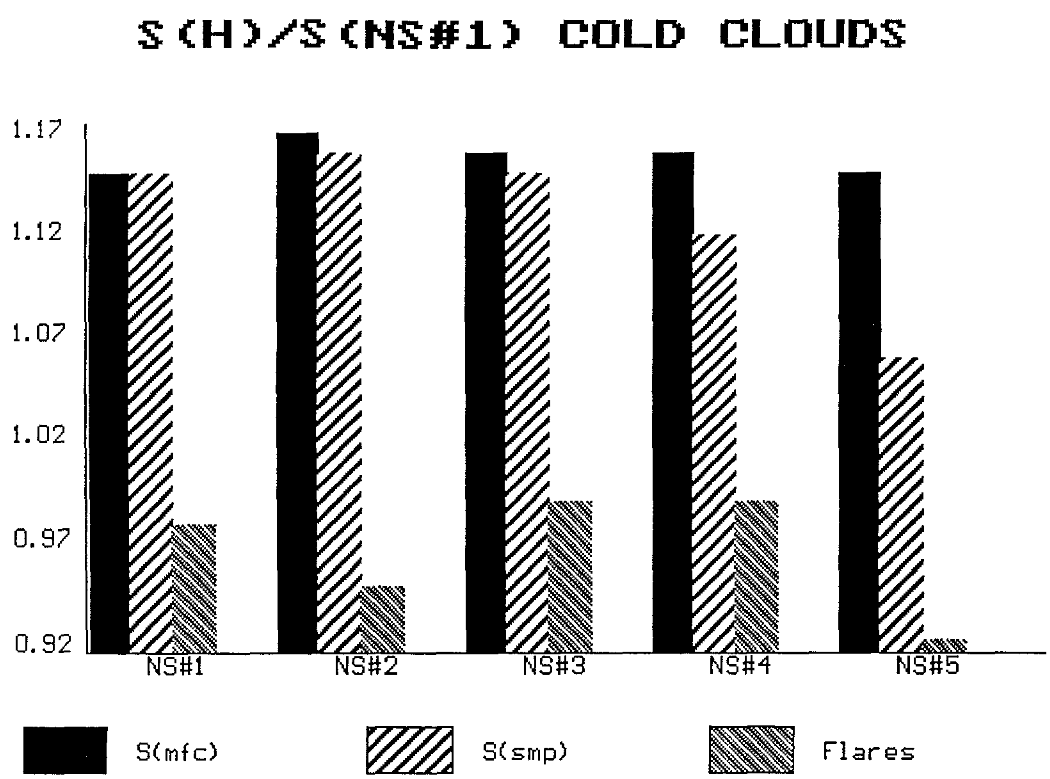

Figure D.5.8.b. - Same as figure D.5.8.a but for cold clouds.

cold clouds. This finding is consistent with a static mode seeding effect. One difference between the results for warm and cold clouds is, however, apparent. For the warm clouds, the seed-no seed ratios tend to decrease with increasing cloud depth in line with the notion that the natural rainfall efficiency increases and the seeding effectiveness decreases with increasing cloud depth. This tendency is also apparent for the cold clouds, but not quite as strongly.

Table D.5.4. - Results of seeding warm clouds produced by Chiang Mai soundings given in table D.3.1.

Sounding	Cloud Base Temp (°C)	Cloud Depth (m)	$S(mfc)$ (A)	Seeding (B)	$S(smp)$ (B)	Seeding (B)
CM930826	19.5	1710	*	*	*	*
CM930527	20.8	1420	*	*	*	*
CM930422	18.0	1200	*	*	*	*
CM930814	20.8	1930	*	*	*	*
CM930809	20.4	2970	20.86	20.92	18.45	18.46
CM930815	20.0	2730	19.91	19.84	16.73	16.77
CM920822	18.8	2800	13.32	13.46	9.30	9.33
CM930807	19.8	2930	5.84	5.83	5.33	5.30
CM930816	20.1	3230	3.49	3.49	3.07	3.06
CM930821	19.3	2860	2.46	2.46	2.25	2.25
CM930813	20.4	3450	2.52	2.52	2.19	2.18

(A) $S(H)/S(N)$ with respect to rain efficiency
(B) $S(H)/S(N)$ with respect to rain on the ground
* Values exceed 100.0 because values for the natural cloud were very small

Table D.5.5. - Results of seeding cold clouds produced by Chiang Mai soundings given in Table D.3.1.

Sounding	Cloud Base Temp (°C)	Cloud Depth (m)	$S(mfc)$ (A)	Seeding (B)	$S(smp)$ (B)	Seeding (B)
CM930507	16.4	4090	*	*	*	*
CM930425	16.1	6480	3.13	3.11	3.13	3.11
CM930808	21.0	5260	1.26	1.26	1.22	1.22
CM930806	19.5	5600	1.19	1.21	1.17	1.19
CM920810	21.1	7330	1.06	1.06	1.06	1.06
CM930606	21.3	7530	1.04	1.02	1.03	1.01

(A) $S(H)/S(N)$ with respect to rain efficiency
(B) $S(H)/S(N)$ with respect to rain on the ground
* Values exceed 100.0 because values for the natural cloud were very small

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D.6 Summary of Results

The key results of the numerical model experiments are summarized as follows:

D.6.1 Seeding Hypothesis

Hygroscopic particle seeding leads to increased precipitation by producing microphysical effects that accelerate the warm rain collision-coalescence process and, thereby, improve the precipitation efficiency of warm and cold convective clouds. No dynamic effects occur as a result of the exothermic or endothermic nature of the hygroscopic particles.

D.6.2 Seeding Chemical

Of the four hygroscopic chemicals investigated, seeding with dry calcium chloride particles produces the largest seed-no seed ratios.

D.6.3 Seeding Particle Size

For clouds with limited lifetime, the largest seed-no seed ratios are achieved with 50-micrometer-radius calcium chloride particles for both cloud base and near cloud top seeding. For clouds of longer duration, the best results are achieved with smaller radius calcium chloride particles: 30-micrometer-radius particles for cloud base seeding and 10-micrometer-radius particles or less for cloud top seeding. Seeding with readily purchased size distributions of calcium chloride results in smaller seed-no seed ratios than seeding with monodisperse particles; nevertheless, observable seed-no seed ratios are achieved.

D.6.4 Seeding Rate

The seed-no seed ratios for calcium chloride seeding increase with increasing seeding concentration or dosage; however, logistical considerations will limit possible increases.

D.6.5 Seeding Location

Cloud base seeding with calcium chloride produces larger seed-no seed ratios than near cloud top seeding.

D.6.6 Seeding Time

Seeding with calcium chloride particles is most effective when conducted early in the life of a growing cloud (about 5 minutes after cloud formation), when the precipitation initiation process can still be influenced.

D.6.7 Clouds

Hygroscopic particle seeding can increase precipitation from both warm and cold clouds.

D.6.8 Hygroscopic Flares

Hygroscopic flares are capable of increasing precipitation from both warm and cold clouds, but their effectiveness depends highly on the existing natural nuclei spectrum.

D.6.9 Overall Assessment

Warm cloud seeding with hygroscopic particles can produce seeding effects that result in measurable increases in precipitation that can be measured.

D.7 Recommendations

Combining the analyses of scientific feasibility with considerations of economic and logistical practicability leads to the following recommendations for the warm cloud seeding demonstration project:

D.7.1 Seeding Agent

Polydisperse calcium chloride particles as purchased are recommended as the seeding agent. Storage and handling procedures that prevent the degradation of the spectra from *S*(*mfc*) to *S*(*smp*) should be instituted. The development or purchase of a hygroscopic particle dispensing system for the warm cloud seeding demonstration project should be pursued. The dispenser should be capable of ejecting the hygroscopic seeding particles from the aircraft at rates ranging from 75 kilograms per minute to 375 kilograms per minute. The dispenser should contain some kind of device, like a stirrer or agitator, which will act to reduce the clumping of the hygroscopic particles.

Monodisperse distributions are not recommended because the cost of acquiring and maintaining such distributions is prohibitive.

Hygroscopic flares are not recommended at this time, despite their very promising results, because: a) their true effectiveness cannot be estimated until data on the nature and variability of the natural nuclei spectrum in the target area are obtained, b) the timing and location of hygroscopic flare seeding must be established by determining when and where clouds naturally develop over the experimental area, and c) the hygroscopic flare seeding operation at very low altitudes in the subcloud layer probably cannot be accomplished in the mountainous terrain of the target area without considerable practice, if at all. Nevertheless, future implementation of this approach should be actively explored because it is potentially more efficient and much less expensive. Therefore, the procurement and installation of a ground-based CCN counter at the AARRP radar site is highly recommended so continuous measurements of CCN can be made.

D.7.2 Seeding Strategy

Seeding should be conducted as soon as the qualification criteria in the target areas are met without regard to or fear that the clouds will grow above the freezing level. Seeding should be conducted as low in the cloud as possible consistent with good flight safety practices. Seeding should be conducted by two CASA aircraft with appropriate time and/or space separation to maximize the seeding concentration. Considering that the maximum payload of each aircraft is 1200 kilograms, that the aircraft customarily fly at 120 knots, and that the seeding material cannot be dispensed in less than 15 minutes, a seeding concentration of 0.0685 gram per cubic meter will result.

D.7.3 Field Studies

The above findings are based almost exclusively on numerical model experiments which, although consistent with other model studies and field experiments conducted elsewhere, do not yet have the benefit of field verification in the proposed target area. Preliminary confirmation of expected physical effects was planned during the 1993 field season, but could not be pursued because of equipment failures. Therefore, it is recommended that the demonstration project include physical studies to confirm the nature and magnitude of predicted effects on individual clouds.

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APPENDIX E

Estimation of Sample Size

Warm Cloud Seeding Demonstration Project

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E.1 Introduction

Appendix D presented the results of a series of numerical modeling experiments concerned with the design of the microphysical aspects of the warm cloud seeding demonstration project. This appendix is concerned with some of the statistical aspects of that design. The results of several related studies which form the basis of the recommended statistical design are presented. These studies had three main objectives: 1) the selection of an efficient experimental design that is feasible to execute, 2) the selection of target area(s) that are compatible with the selected experimental design, and 3) the determination of the number of samples needed to ascertain with confidence the sign and magnitude of a seeding effect on rainfall if, in fact, one is produced. Implicit in these studies is the choice of statistical methodologies that will be used to evaluate the warm cloud seeding demonstration project.

E.2 The Experimental Design

From the outset, it was decided to adopt, if feasible, the alternating target or randomized crossover experimental design. According to this design, one of a pair of targets is randomly selected for seeding each time an experimental unit is qualified. This design has several major advantages. First, it maximizes the frequency of seeding operations during the current period of below normal precipitation. Second, the efficiency of this design permits the experiment to reach statistical significance with a relatively small number of samples, even if the rainfall in the target pair is not well correlated. If the target areas are well correlated and/or have well correlated control areas, the required number of samples is considerably smaller.

To qualify as targets in a randomized crossover design, the target areas must be separated by a buffer zone and oriented to the prevailing wind in such a way that makes the seeding of one target unlikely to contaminate the other target. The target pair also must have a relatively high frequency of simultaneous occurrence of seeding opportunities. Finally, it is desirable, but not absolutely necessary, for the statistical characteristics of the rainfall in the two target areas to be reasonably similar and reasonably well correlated.

E.3 The Search for Suitable Target Areas

The main tool in the search for suitable target areas was the data from the AARRP 10-centimeter Doppler weather radar. Radar data was used instead of rainfall data because it is continuous in space and time, and, therefore, offers a wider choice of potential target areas. Accordingly, Dr. Daniel Rosenfeld of the Hebrew University of Jerusalem, a key scientist working on the AARRP, processed 11 months of radar data collected during the 1991-1993 field seasons into 3-hourly radar-rainfall maps. Rainfall values for every 10- by 10-kilometer square during each 3-hour period were calculated using the tropical *Z-R* relationship of $Z=300*R**1.4$.

The selection of potential target areas was guided by several factors: 1) the western quarter of the area was avoided because the rain was known to come mainly from stratiform clouds with shallow tops that could not be observed by radar in their entirety, 2) areas with similar topography and radar range were favored, and 3) areas which were observed to have similar cloud conditions by AARRP scientists, particularly Reclamation scientist Curt Hartzell, were also favored. When potential target areas were selected, the rain data for these areas were extracted from the radar-rainfall maps and the appropriate statistical rainfall characteristics were calculated. Target area pairs whose rain data compared favorably were then fine tuned to maximize their statistical relationships. Candidate target area pairs were then compared, and the best of these were selected as target areas for the warm cloud seeding demonstration project.

This guided search for target areas resulted in the selection of two pairs of target areas, which will be referred to as the western target area pair, TA-W1 and TA-W2; and the eastern target area pair, TA-E1 and TA-E2. These target area pairs are shown on a typical radar-rainfall map (fig. E.3.1). The western target area pair was found to be best for the 3-hour period 0900-1200 LST; the eastern target pair was best for the 3-hour period 1500-1800 LST. The conduct of more than one experiment per day was feasible because both a space and time buffer existed between the target pairs. The target area pairs were oriented generally north-south, so contamination was not likely by the prevailing winds, whose frequency peaked in the west-northwest to west-southwest quadrant. Having selected the target area pairs, upwind control areas and downwind study areas were also selected. Table E.3.1 gives the names of and relationships between target areas in the two target area pairs. All the control and target areas are 30 by 30 kilometers in area; DW-E1 is 40 by 40 kilometers in area, and DW-E2 is 40 by 50 kilometers in area.

Table E.3.1. - Target area names and relationships.

Target Pair		Upwind Control	Target Area	Downwind Study Area
West	North	CA-W1	TA-W1	DW-W1 (TA-E1)
	South	CA-W2	TA-W2	DW-W2 (TA-E2)
East	North	CA-E1 (TA-W1)	TA-E1	DW-E1
	South	CA-E2 (TA-W2)	TA-E2	DW-E2

Table E.3.2 gives the characteristics of the rainfall in the control, target, and downwind areas. Table E.3.2 shows that 1) the mean rainfall and standard deviation are greater in the east target pair than in the west target pair, 2) the mean rainfall and standard deviation within each target pair are about the same, and 3) the mean number of rain days per month is slightly greater in the east than it is in the west.

									TA-E1	TA-E1									
.016	.259	.801	.736	.495	.986	3.018	1.550	.554	.249	.120	.130	.167	.104	.010	.036	.010	-.001	.016	.125
					TA-W1														
.565	.116	.358	1.482	.576	.176	.509	.764	.940	.197	.165	.031	.157	.094	.037	.068	.154	-.001	-.001	.382
1.488	1.463	1.687	.666	.305	.187	.156	.239	.863	.518	.156	.105	.035	.152	.030	.015	.061	-.001	-.001	.006
.281	.451	2.236	1.517	.283	.415	.142	.099	.467	1.984	1.241	.160	.247	.207	.047	.000	.049	.358	.128	-.001
.288	.134	.441	.617	.101	.157	.736	.494	.065	2.275	11.302	7.881	2.296	.996	.671	.348	.047	.076	.027	.045
				RADAR *															
.266	.419	.056	.022	.105	.026	.041	1.063	.954	.735	2.523	10.380	16.380	8.045	6.716	3.534	.338	.817	1.910	.527
						TA-W2						TA-E2							
.259	.390	.355	.014	.050	.118	.107	.639	1.571	5.500	1.912	7.354	14.337	14.057	6.539	8.596	1.658	.330	1.901	.818
.082	.048	.067	.036	.078	.026	.173	.568	2.350	6.176	5.132	4.421	6.708	6.570	18.015	14.133	4.995	.701	5.008	.954
.007	.017	.223	.005	.043	.244	.487	.423	.347	2.704	5.118	1.823	1.236	5.253	7.486	14.963	2.988	.325	.772	1.320
.791	.039	1.024	.056	-.001	.101	1.845	1.227	.516	.403	1.373	1.249	1.110	3.698	6.310	1.306	1.412	.081	2.159	4.694

Figure E.3.1. - Typical 3-hourly radar-rainfall map showing the two pairs of warm cloud seeding target areas.

Table E.3.2.- Rainfall characteristics of the control, target, and downwind areas.

Area	Daily Rain Amount (mm)			No. of Days per Month	
	Mean	Std. Dev.	Maximum	Mean	Std. Dev.
CA-W1	0.11	0.38	3.12	12.1	7.0
TA-W1	0.15	0.57	6.40	18.6	8.1
DW-W1	0.07	0.33	3.69	13.2	7.7
CA-W2	0.08	0.41	5.16	11.9	7.0
TA-W2	0.13	0.61	6.47	15.3	8.5
DW-W2	0.15	0.55	5.96	15.2	7.9
CA-E1	0.45	1.33	11.33	18.9	7.7
TA-E1	0.48	2.05	26.47	18.1	6.6
DW-E1	0.30	1.28	20.19	16.6	7.0
CA-E2	0.33	1.07	14.06	17.2	7.0
TA-E2	0.58	2.06	30.20	17.3	7.5
DW-E2	0.50	1.47	15.36	16.0	6.3

Figures E.3.2.a and E.3.2.b give the mean number of rain days per month by rainfall class in the west and east target pairs, respectively. The figures show that from one-third to one-half of the days in both target pairs have no rain, and the frequency of rain days sharply peaks for rains less than 0.26 millimeter. Figures E.3.3.a and E.3.3.b give the percent of total rain per month by rainfall class in the west and east target pairs, respectively. These figures show that the rains from 1.0 to 2.6 millimeters make the greatest contribution to mean total monthly rain.

Finally, table E.3.3 presents the frequency of simultaneous occurrence of rain events and correlation coefficients between relevant targets. These results are very encouraging. Except for CA-E2/TA-E2, all relevant target combinations have respectable correlation coefficients. The correlation between target pairs is 0.66 and 0.71 for the west and east target pairs, respectively.

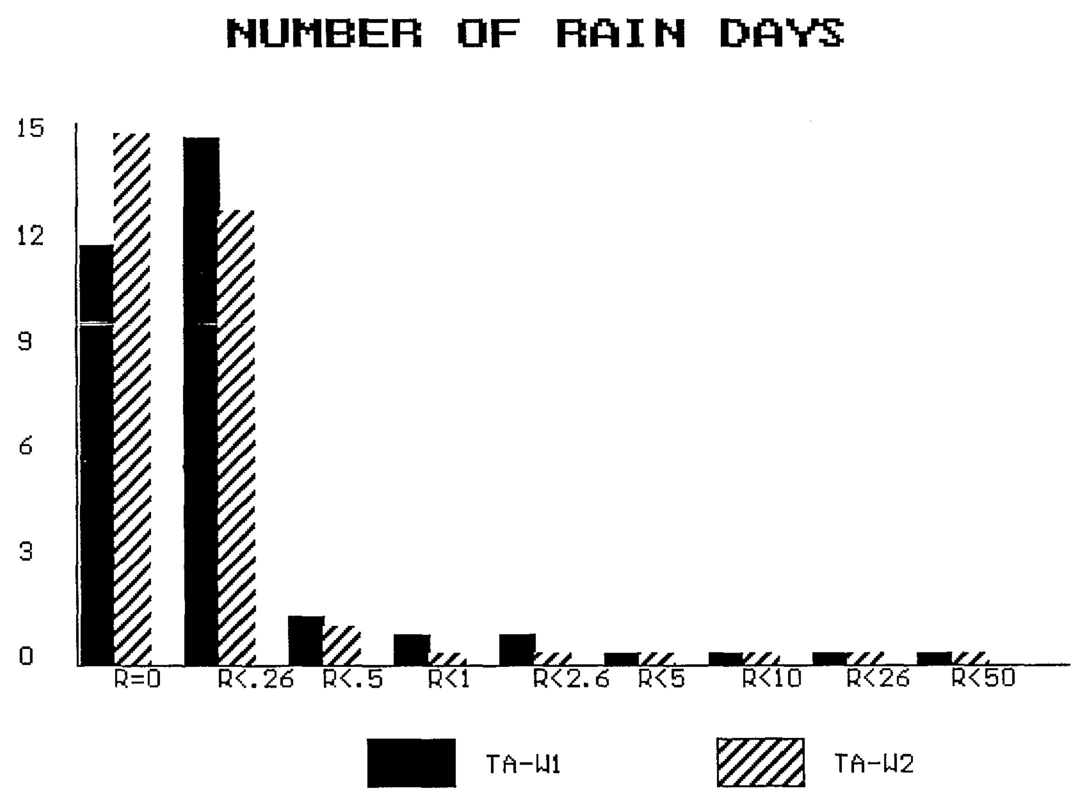

Figure E.3.2.a. - Mean number of rain days per month by rainfall class for the west target pair.

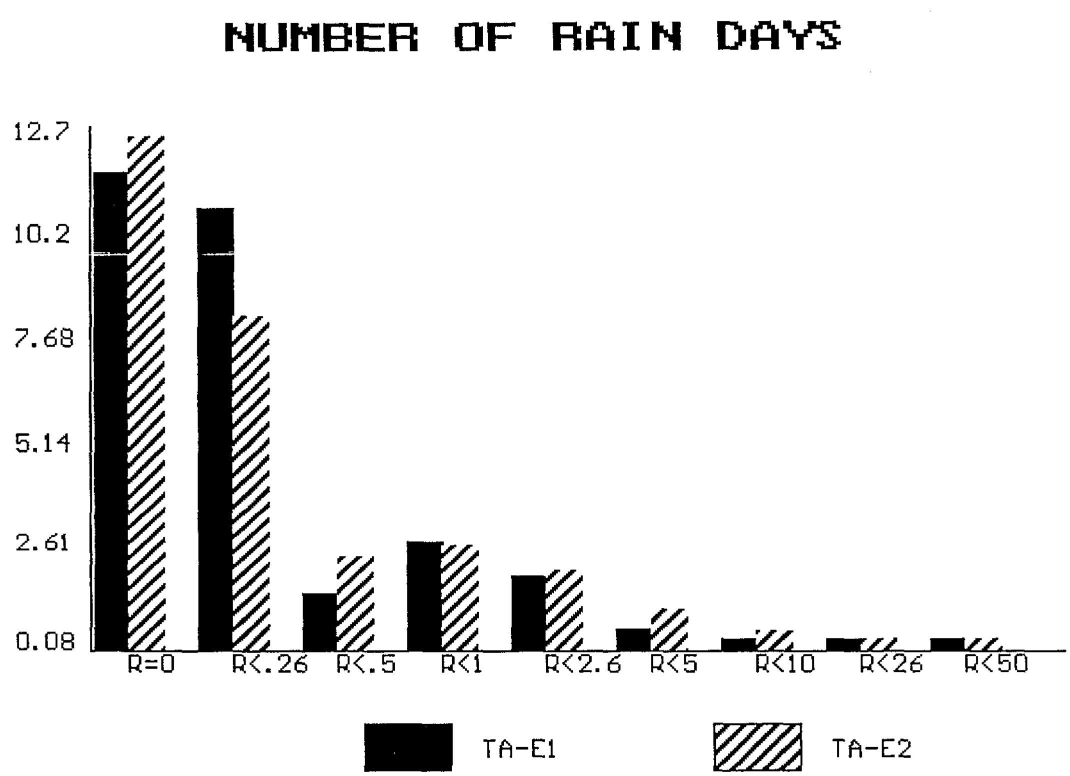

Figure E.3.2.b. - Mean number of rain days per month by rainfall class for the east target pair.

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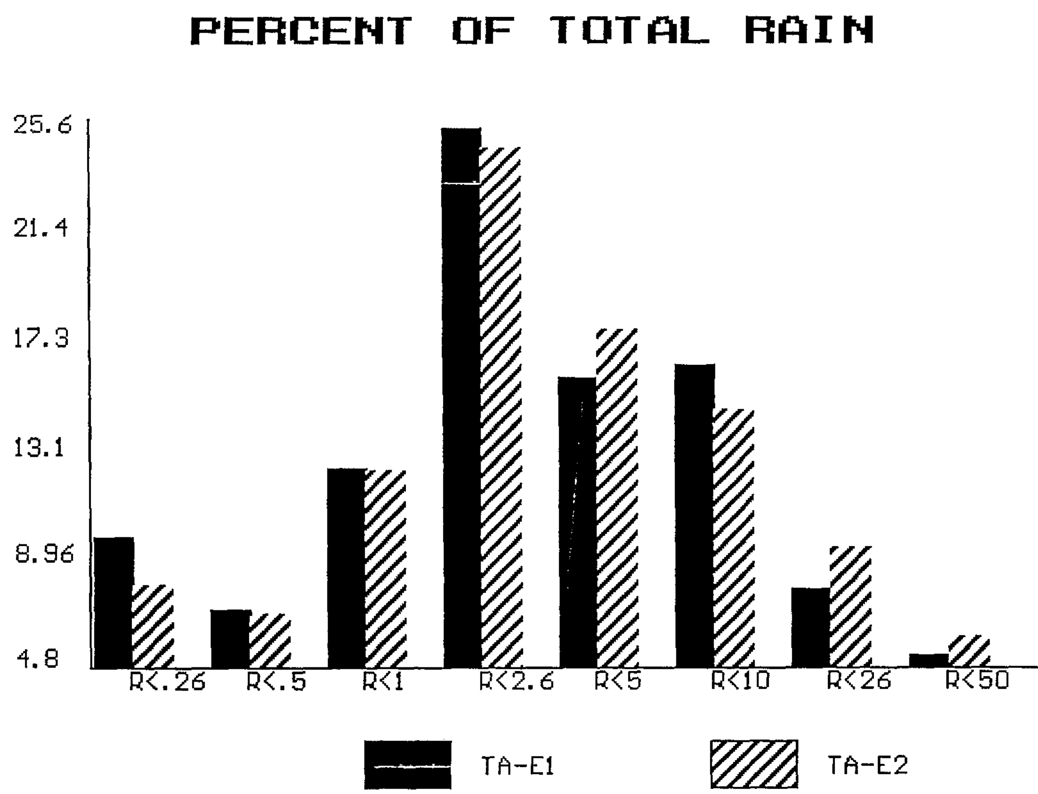

Figure E.3.3.a. - Percent of total rain per month by rainfall class for the west target pair.

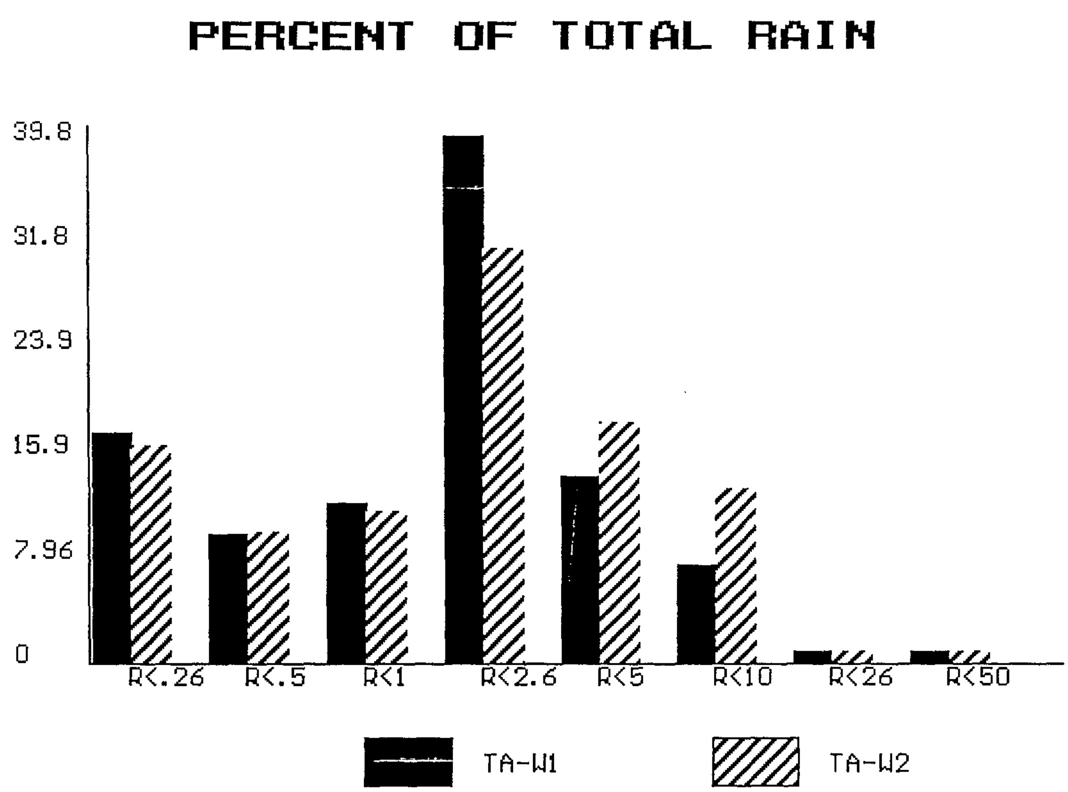

Figure E.3.3.b. - Percent of total rain per month by rainfall class for the east target pair.

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Table E.3.3. - Frequency of simultaneous occurrence of rain events and correlation coefficients between relevant targets.

Targets	Number of Occurrences (Y = Rain, N = No Rain)				Correlation Coefficient
	Y/Y	Y/N	N/Y	N/N	
TA-W1/TA-W2	167	1	38	131	0.66
CA-W1/TA-W1	131	74	2	130	0.54
CA-W2/TA-W2	125	43	6	163	0.63
TA-W1/DW-W1	144	1	61	131	0.87
TA-W2/DW-W2	147	20	21	149	0.60
TA-E1/TA-E2	179	11	20	127	0.71
CA-E1/TA-E1	191	8	17	121	0.64
CA-E2/TA-E2	174	16	15	132	0.22
TA-E1/DW-E1	175	7	24	131	0.73
TA-E2/DW-E2	161	15	29	132	0.51

The above data confirm that the implementation of a randomized crossover design is feasible. In a later section, these data will be used to determine the number of samples needed to ascertain with confidence hypothetical seeding increases in rainfall.

E.4 Estimation of Sample Size

Monte Carlo simulations were used as the vehicle for estimating sample size requirements using the rainfall data sets for the pairs of target areas described in section E.3. A two-step randomization procedure was used to generate 500 seed-no seed data sets (simulated cloud seeding experiments) for each set of initial conditions, that is, target area pair, sample size, seeding model, and treatment factor. These data sets were used in the statistical analyses. In the first step, the target area was randomly selected for treatment, either the north or south target of the target pair being studied. In the second step, a separate randomization kernel was used to randomly select the data point to treat in the randomly selected target. The randomization process in the first step was constrained by not allowing more than three consecutive random selections of the same target. The randomization process in the second step was unrestricted, and the sampling was done with replacement. The simulations in each case started with a sample size of 60, which was then incremented by 60 until a probability of detection or power of the test of 0.90 at a significance level (alpha) of 0.05 was reached (see appendix A for definitions of these terms). A sample size increment of 60 was chosen because it was estimated from the data analyses in section 3 that about 60 seeding opportunities would occur during the June 15 to October 14 warm cloud seeding field season.

E.4.1 Seeding Models

Two seeding models were used to apply a treatment to the randomly selected sample. Seeding model one, called the MULTIPLICATIVE model, was based on the conventionally-used multiplicative model, that is, an SMF (seeding multiplicative factor) was applied to the randomly selected sample. Seeding simulations were done for SMF values of 1.05, 1.10, 1.15, and 1.20. With this seeding model, the rainfall data sets were limited to periods when rain occurred in both targets of the target pair, that is, rain-rain events only.

Seeding model 2, called the MULT+ADD model, was inspired by the results of numerical model cloud seeding experiments (see appendix D) and general cloud seeding experience. This model is based on two important premises: 1) that seeding can induce clouds to rain that would not rain naturally, and 2) the percentage increase in rain caused by seeding decreases with increasing natural rainfall amount. Seeding simulations with this model were also done for overall SMF values of 1.05, 1.10, 1.15, and 1.20; however, the SMF values consisted of a variable multiplicative factor and a fixed additive factor (hence, the name MULT+ADD model). The additive factor in each case was equal to 4 percent of the mean rainfall amount in the data set being used. The multiplicative factor accounted for the balance of the overall SMF, that is 1.01 for an SMF of 1.05, 1.06 for an SMF of 1.10, etc. The multiplicative factor was largest for the smallest recorded rainfall amount and linearly decreased to a value of 1.0 for a natural rainfall amount equal to the mean rainfall plus one standard deviation. The multiplicative factor applied to the smallest rainfall amount was adjusted such that the integrated effect was equal to 1.01, 1.06, 1.11, and 1.16 for the overall SMF cases of 1.05, 1.10, 1.15, and 1.20, respectively. With this seeding model, the rainfall data sets included all rain-rain, rain-no rain, and no rain-rain events. The no rain-no rain events had to be excluded because of the possibility that rain did not occur because of the lack of clouds.

Figure E.4.1 illustrates how an effective seeding multiplication factor of 1.10 for the two seeding models is applied as a function of unseeded rainfall amount. The mean and standard deviation of the hypothetical unseeded rainfall amounts are 0.85 and 2.549 millimeters, respectively.

E.4.2 Analysis Method

A number of different parametric and non-parametric statistical methods were used to estimate *P*-values and the power of the test for each simulated experiment and set of experiments. The statistical approach that was uniformly most powerful and consistent was the MRPP (Multi-Response Permutation Procedure) (Mielke et al., 1976; Mielke et al., 1981). Only the application of this approach and the subsequent results will be presented here.

The two data sets submitted for MRPP evaluation in each case took advantage of the relationship (correlation) between target areas in a target pair. They were constructed in the following manner:

1. When the north target was seeded, the data set consisted of the difference between the actual seeded rainfall and the predicted rainfall that would have occurred in the absence of seeding. The predicted non-seeded rainfall was estimated from the regression equation of north rain on south rain forced through the origin.

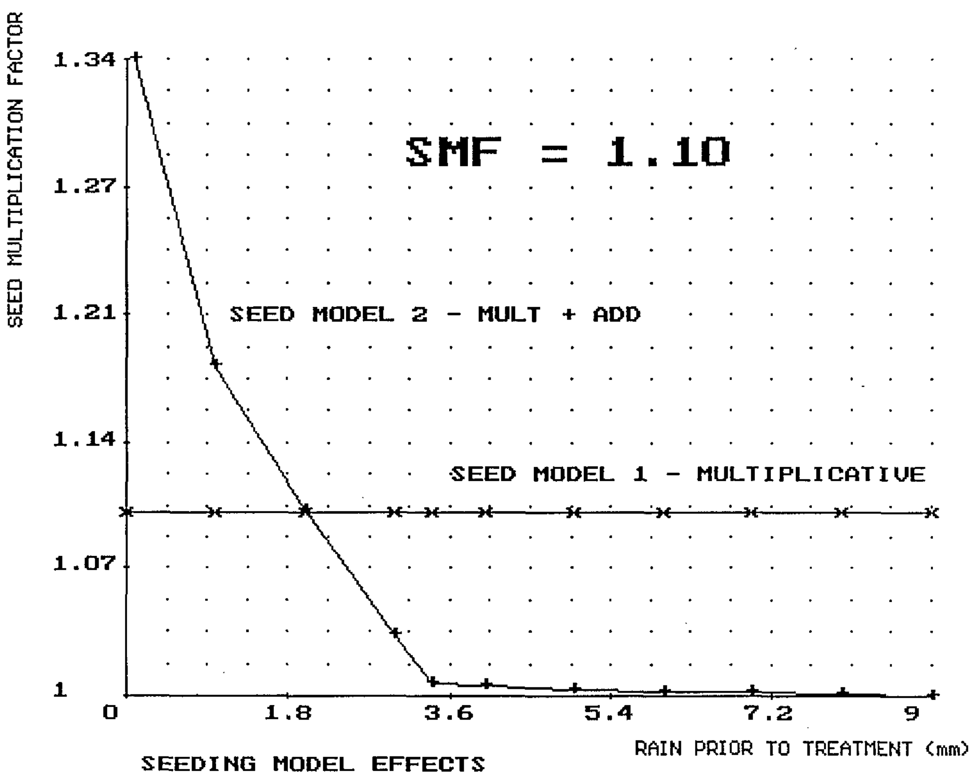

Figure E.4.1. - Effective seeding multiplication factor as a function of unseeded rainfall amount for seeding models 1 and 2, and an integrated seeding multiplication factor of 1.10. The mean and standard deviation of the hypothetical natural rainfall amounts are 0.85 and 2.549 millimeters, respectively.

2. When the south target was seeded, the data set consisted of the difference between the predicted rainfall that would have occurred in the absence of seeding and the actual seeded rainfall. The predicted non-seeded rainfall was estimated from the regression equation of south rain on north rain forced through the origin.

MRPP testing of these data sets is conceptually equivalent to a *T*-test that these differences are not equal to zero and, indeed, the application of the *T*-test in this manner gave results consistent with those of the MRPP test.

E.4.3 Sample Size Estimates

Figures E.4.2.a and E.4.2.b present the results of the statistical simulations for the west target pair using the MULTIPLICATIVE and MULT+ADD seeding models, respectively. Figures E.4.3.a and E.4.3.b present the results for the east target pair. An examination of these results indicates the following:

1. Sample size requirements are smaller for the MULT+ADD seeding model than the MULTIPLICATIVE seeding model in all cases.

2. Sample size requirements for the east target pair are greater than those for the west target pair for both seeding models, primarily because the variability of the rain data in the east target pair is greater (table E.3.2).

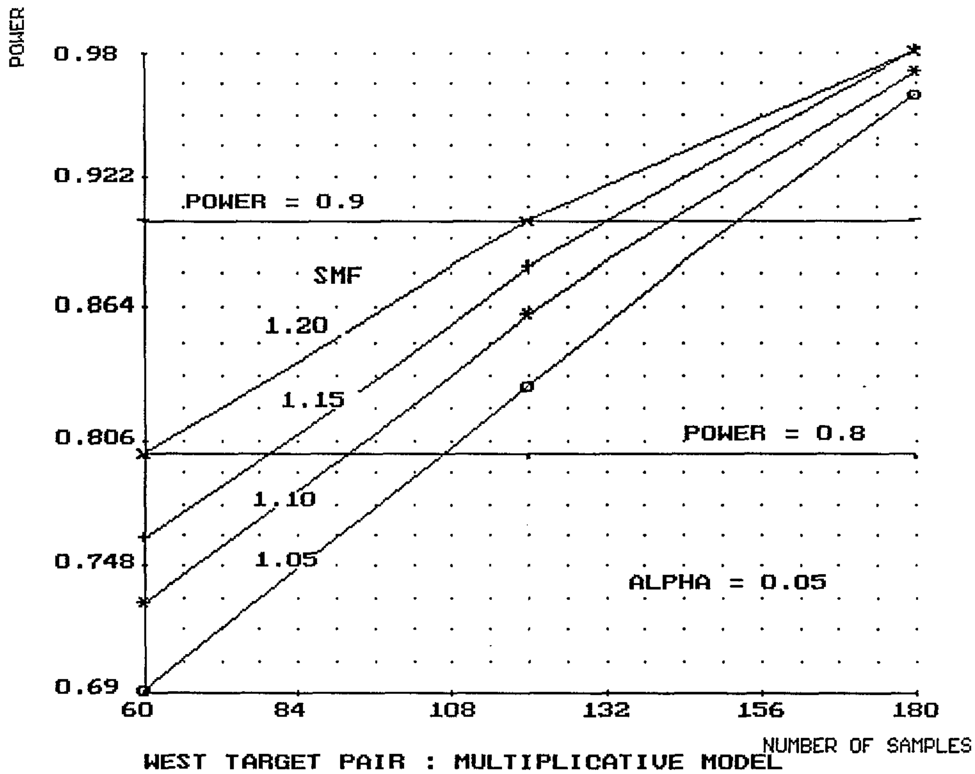

Figure E.4.2.a. - Power of test versus sample size as a function of seeding multiplication factor (MULTIPLICATIVE seeding model) for the west target pair.

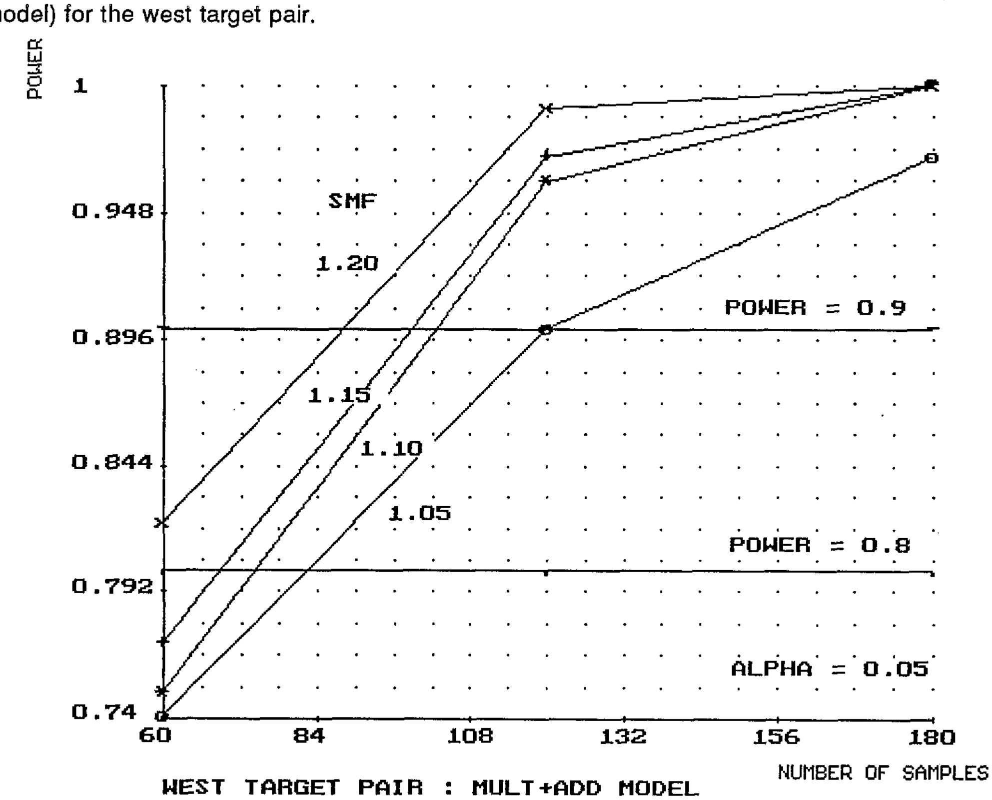

Figure E.4.2.b. - Power of test versus sample size as a function of seeding multiplication factor (MULT+ADD seeding model) for the west target pair.

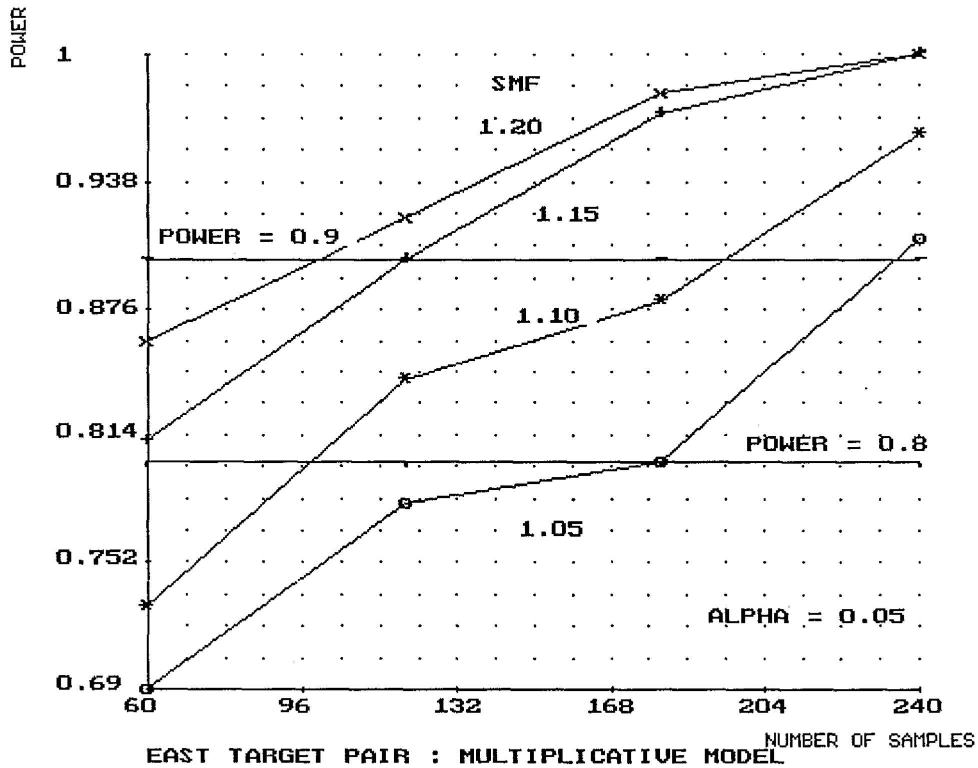

Figure E.4.3.a. - Power of test versus sample size as a function of seeding multiplication factor (MULTIPLICATIVE seeding model) for the east target pair.

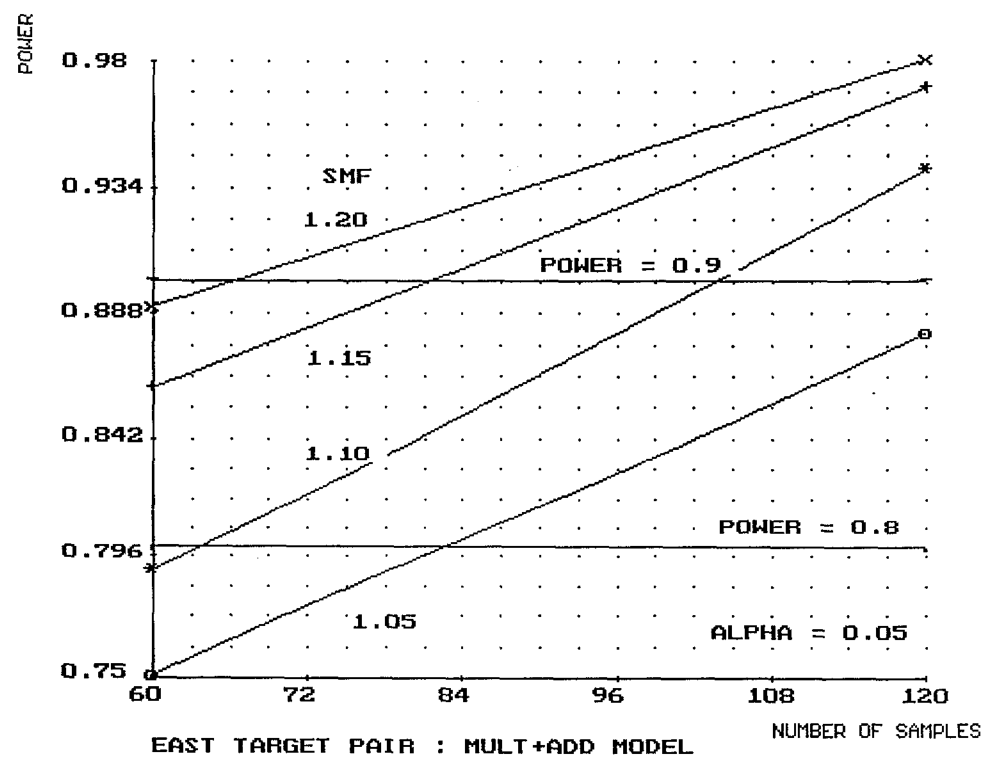

Figure E.4.3.b. - Power of test versus sample size as a function of seeding multiplication factor (MULT+ADD seeding model) for the east target pair.

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3. Sample size requirements increase as SMF decreases.

4. Assuming, for example, that seeding increases rainfall by 10 percent (SMF = 1.10), the sample sizes required to achieve probabilities of detection of 0.80 and 0.90 at a significance level of 0.05 are about:

Target Pair	Power	Sample Size for Seeding Model: MULTIPLICATIVE	Sample Size for Seeding Model: MULT + ADD
West	0.80	93	75
	0.90	144	102
East	0.80	99	64
	0.90	195	104

These results indicate that obtaining the required number of samples would take from 2 to 3 years, assuming that 60 seeding opportunities occur per year and that all are successfully implemented. It is conservatively estimated that obtaining the required number of samples will likely take 4 to 5 years because the number of opportunities is likely to vary and some seeding opportunities will be missed because of errors in execution or equipment failures. *It is emphasized that the number of samples will determine the duration of the experiment.*

E.5 References

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APPENDIX F

Hydrometeorological Trends in Northern Thailand

F.1 Introduction

Thailand has a progressive agricultural system and a functional water management system. The growing need for water is most heavily related to the needs of a growing population and Thai economy, which needs more water to meet expanding agricultural, energy, municipal, and industrial needs. Water pollution caused by agricultural, industrial, and human waste is also a growing problem because Thailand depends heavily on surface water supplies to meet water demands. Large quantities of surface water must be used to address these water quality problems and salt (sea) water intrusion in some major river and irrigation systems.

In northern Thailand, major reservoirs, including the Bhumibol and Sirikit reservoirs, provide water to extensive irrigated areas in the central plains devoted to growing water intense crops (the main crop is rice) in the dry season as well as the wet season (fig. F.1.1). These multipurpose reservoirs are also operated to handle potential floods caused by an occasional tropical typhoon, to provide water for municipal and industrial purposes, to generate hydroelectric power, and to dilute lower river pollution episodes. The irrigated areas represent only about 15 percent of the nation's irrigated lands, but they produce nearly 50 percent of the nation's crop value. The economy of the nation is strongly tied to the needs served by the reservoirs in northern Thailand.

Being heavily dependent on surface water supplies, the adequacy of water resources in northern Thailand are very reliant on the rainfall in each month, season, and year. The southwest monsoon or wet season (May-October), brings up to 80 percent of the yearly amount of rain. The monsoon can begin early or end late or be weak, which causes the rainfall amount to vary. Within the wet season, dry periods of 1 to 4 weeks are common from June to August. The time and space variability of rainfall often results in regional water shortages and severe water management problems.

Hydrometeorological trends in the Bhumibol and Sirikit catchment areas are examined to better understand the need for and role of weather modification in the management of water resources of northern Thailand. Knowledge of the hydrometeorological trends and the relationships between hydrometeorological parameters are also valuable in assessing the feasibility of conducting a secondary hydrological evaluation of the rainmaking demonstration project based on historical data.

F.2 Rainfall Trends

Figures F.2.1 and F.2.2 show the long-term (1911-1992) rainfall trends in the Bhumibol and Sirikit catchment areas, respectively. Rainfall in the Bhumibol catchment area is represented by the rainfall at Chiang Mai, and rainfall in the Sirikit catchment area is represented by the rainfall at Nan. The long-term mean rainfalls are 1200 and 1242 millimeters in the Bhumibol and Sirikit catchment areas, respectively; both areas have standard deviations equal to about 20 percent of the means. The correlation coefficient between rainfall in the two catchment areas is 0.75.

It is important to note that the mean annual rainfall in the Bhumibol and Sirikit catchment areas was higher prior to commissioning of the Bhumibol and Sirikit dams than afterward. Prior to 1963, the mean annual rainfall in the Bhumibol catchment area was 1224 millimeters, but afterward it was 1159 millimeters. Prior to 1972, the mean annual rainfall in the Sirikit catchment area was 1252 millimeters, but afterward it was 1213 millimeters. Data characteristics, such as the mean, that cover the periods after the dams were commissioned, are referred to as 'modern' record values.

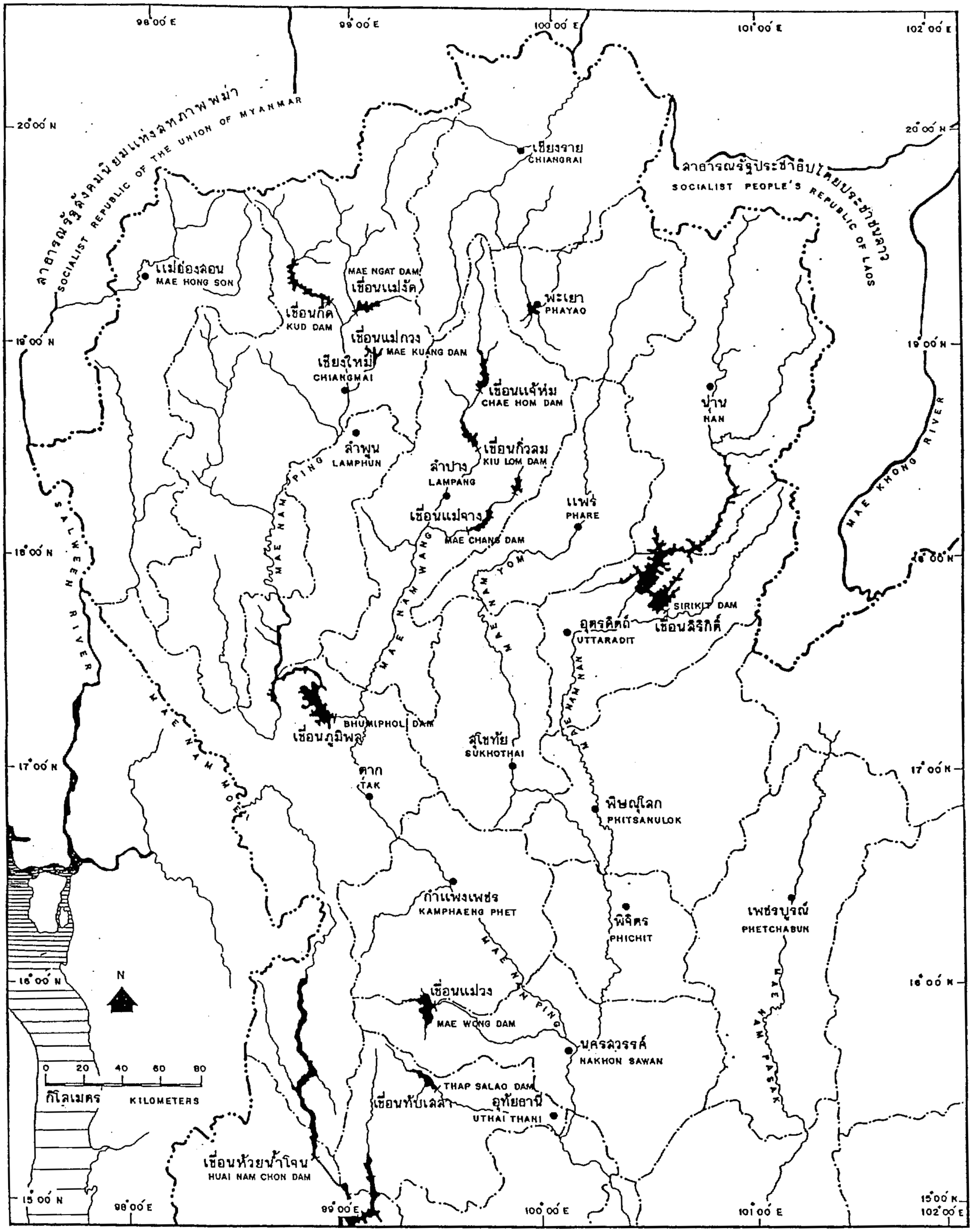

Figure F.1.1. - Map of northern Thailand showing the major reservoirs and river systems.

2.3(?)

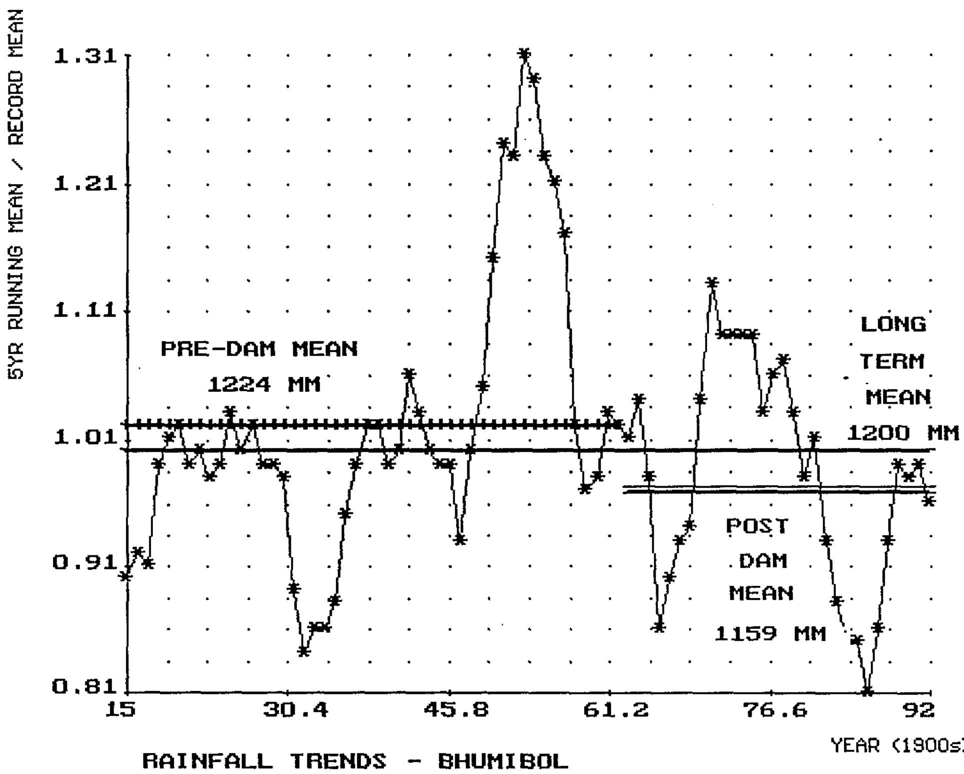

Figure F.2.1. - Long-term (1911-1992) rainfall trend in the Bhumibol catchment area.

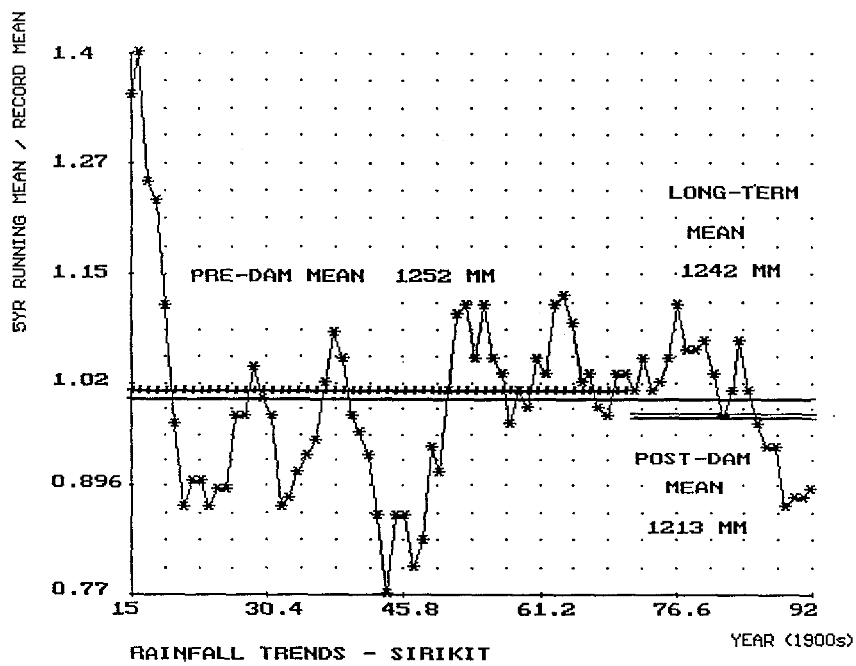

Figure F.2.2. - Long-term (1911-1992) rainfall trend in the Sirikit catchment area.

F.3 Hydrological Trends

Figures F.3.1 and F.3.2 show the trends in reservoir storage and reservoir level, respectively, for both the Bhumibol and Sirikit reservoir systems. The mean annual reservoir storages for Bhumibol and Sirikit are 8337 and 5789 MCM (millions of cubic meters), respectively. The mean annual reservoir levels for Bhumibol and Sirikit are 241.3 and 145.1 meters, respectively. Figures F.3.1 and F.3.2 show that the reservoir level and storage for both Bhumibol and Sirikit were below normal from 1986 to the present except for 1989, which occurred because of above normal rain in 1988 (fig. F.3.3). As a point of reference, table F.3.1 gives key reservoir and power data for the Bhumibol and Sirikit reservoir systems (EGAT, 1989).

Table F.3.1. - Reservoir and power data for the Bhumibol and Sirikit reservoir systems.

Reservoir Parameter	Bhumibol	Sirikit
Catchment area (km^2)	26,386	13,300
Average Annual Inflow (MCM)	5,780	5,169
Normal High Water Line (NHWL)(m)	260	162
Storage at NHWL (MCM)	13,462	9,510
Drawdown level (m)	213	128
Average annual energy (GWh)	1,200	1,000
Irrigable area (Rai)	> 7,600,000	

It is interesting to note that at the time that the Thailand Weather Modification Assessment was conducted in September 1986, both the storage and reservoir level in the Sirikit were above normal by about 6 percent and 15 percent, respectively. In the Bhumibol, the reservoir level was about normal and the storage was 11 percent above normal. Both the Bhumibol and Sirikit reached their all-time low values in June 1992; in the Bhumibol, the reservoir level and storage were 213.8 meters and 3902 MCM, respectively, and in the Sirikit, they were 129.2 meters and 2997 MCM, respectively. Thus, in June 1992, both the Bhumibol and Sirikit were critically close to their respective drawdown levels.

F.4 Hydrometeorological Relationships

F.4.1 Bhumibol Reservoir System

Figure F.4.1 shows the trends in rainfall and inflow for the Bhumibol reservoir system. Focusing on the past decade, the figure shows that inflow into the reservoir was below its modern normal for the entire period. Rainfall, on the other hand, was below its modern normal from 1982 to 1988, and above its modern normal since then. The relationship between monthly inflow and monthly rainfall is:

$$INFLOW = 89.34 + 4.09 * RAINFALL$$

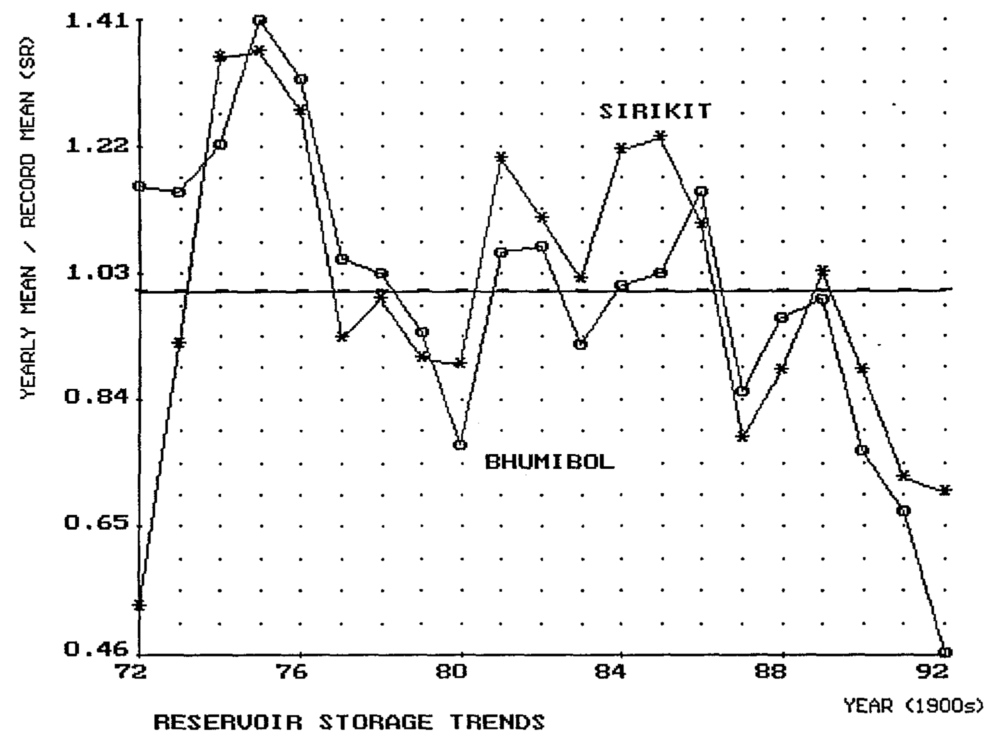

Figure F.3.1. - Reservoir storage trends in the Bhumibol and Sirikit reservoir systems.

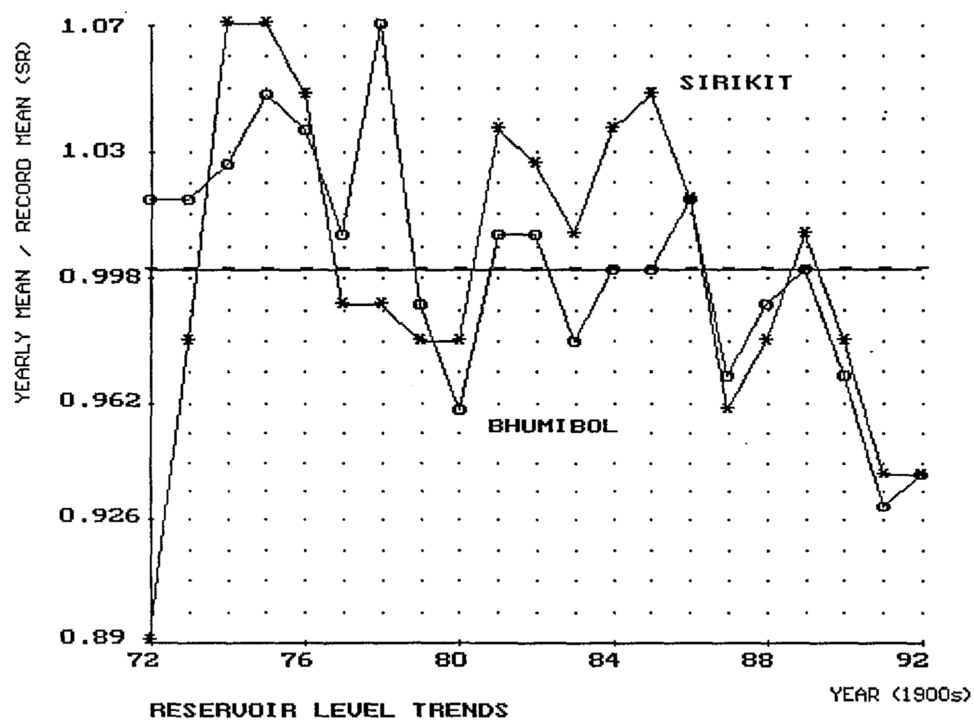

Figure F.3.2. - Reservoir level trends in the Bhumibol and Sirikit reservoir systems.

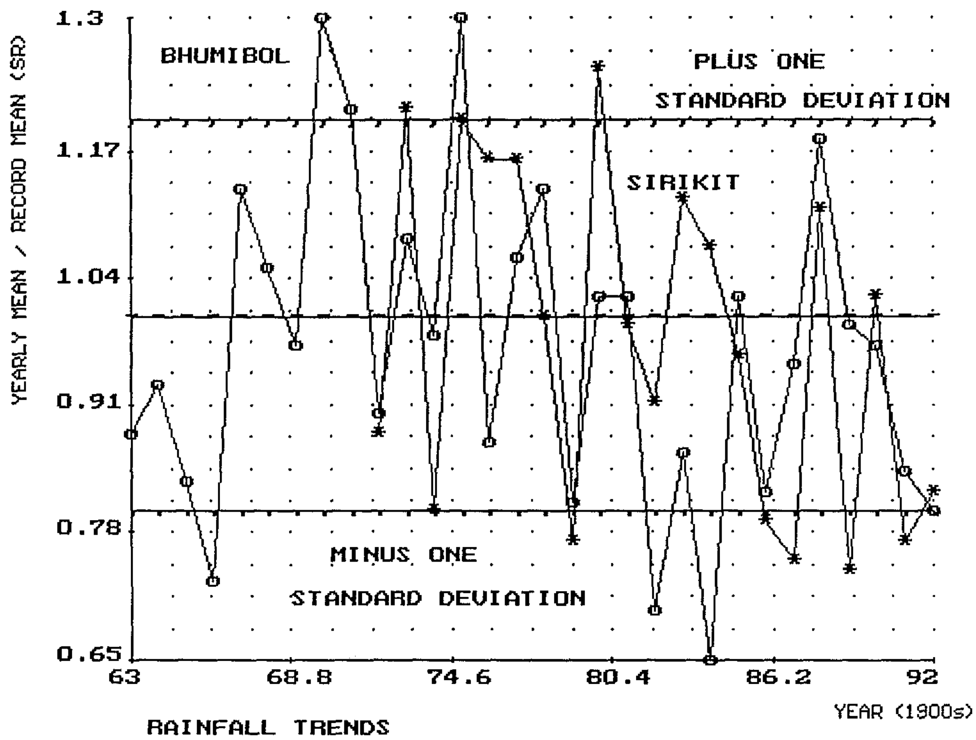

Figure F.3.3. - Annual rainfall in the Bhumibol and Sirikit catchment areas since the reservoirs were commissioned.

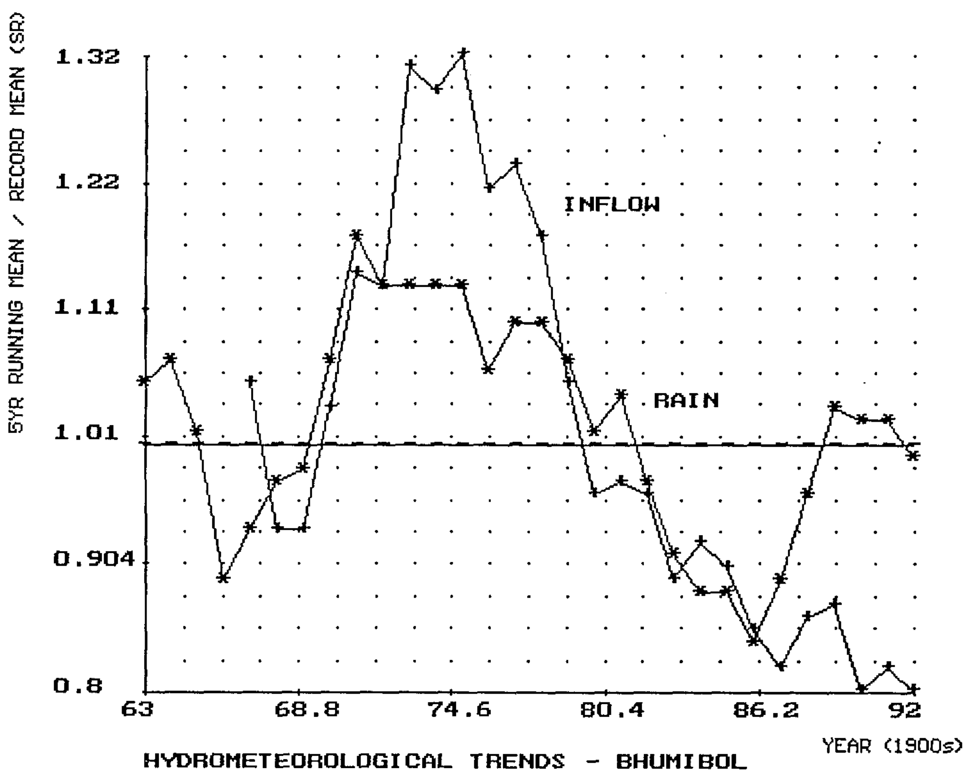

Figure F.4.1. - Hydrometeorological (rain and inflow) trends in the Bhumibol reservoir system.

with a correlation coefficient of 0.72. No meaningful relationship could be found between inflow and outflow, or rainfall and outflow, or inflow and storage, etc., which is not unusual for reservoir systems that have a storage capacity much larger than the average annual inflow.

A plot of the normalized inflow divided by the normalized rainfall (fig. F.4.2) indicates that the percentage of rain falling in the catchment area that reached the reservoir steadily decreased since about 1984. This finding is confirmed by the double mass analysis for Bhumibol (fig. F.4.3), which shows a distinct break in the curve starting in about 1984.

Explaining the cause of this result is beyond the scope of this study; however, a conversation with an EGAT official in 1988 during a discussion of potential sites for the AARRP field experiments provides a clue to a plausible explanation. At that time, a site in the northern part of the Bhumibol catchment area was contemplated. However, based on this discussion, the site was moved to the southern catchment area because of the caution by the EGAT official that much of the water produced in the northern catchment area would not reach Bhumibol reservoir. It was explained that water produced in the northern catchment area would be captured by many small reservoirs, either existing or planned.

F.4.2 Sirikit Reservoir System

Figures F.4.4, F.4.5, and F.4.6 show comparable trends and relationships for the Sirikit reservoir system. Again, focusing on the past decade, these figures show that both the inflow into the reservoir and the rainfall were below their modern normal since 1986. The relationship between monthly inflow and monthly rainfall is:

$$INFLOW = 27.07 + 3.50 * RAINFALL$$

with a correlation coefficient of 0.71. No meaningful relationships were found between the other reservoir parameters because the Sirikit reservoir system has a storage capacity that is much larger than the average annual inflow.

The plot of the normalized inflow divided by the normalized rainfall (fig. F.4.5) indicates that the percentage of rain falling in the catchment area that reached the reservoir steadily decreased since about 1985. This observation is confirmed by the double mass analysis for Sirikit (fig. F.4.6), which shows a distinct break in the curve starting in about 1986. It is likely that the cause of this result for the Bhumibol reservoir system is also operative here.

F.4.3 Conclusions and Recommendations

F.4.3.1 Conclusions

1. No meteorological drought exists in northern Thailand; rather, a hydrological drought exists in northern Thailand.

2. The rainfall amounts in northern Thailand in recent years have been somewhat below normal, but well within natural variability. The rainfall amounts are not low enough to account for the dramatic decline in Bhumibol and Sirikit reservoir levels.

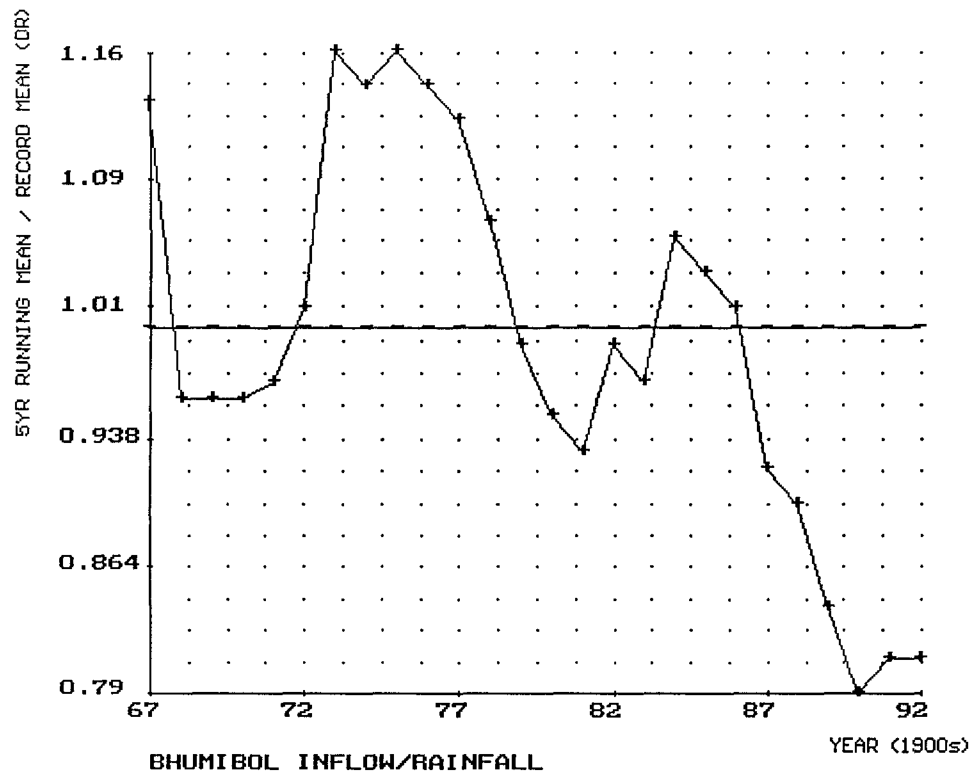

Figure F.4.2. - Normalized ratio of inflow to rainfall in the Bhumibol reservoir system.

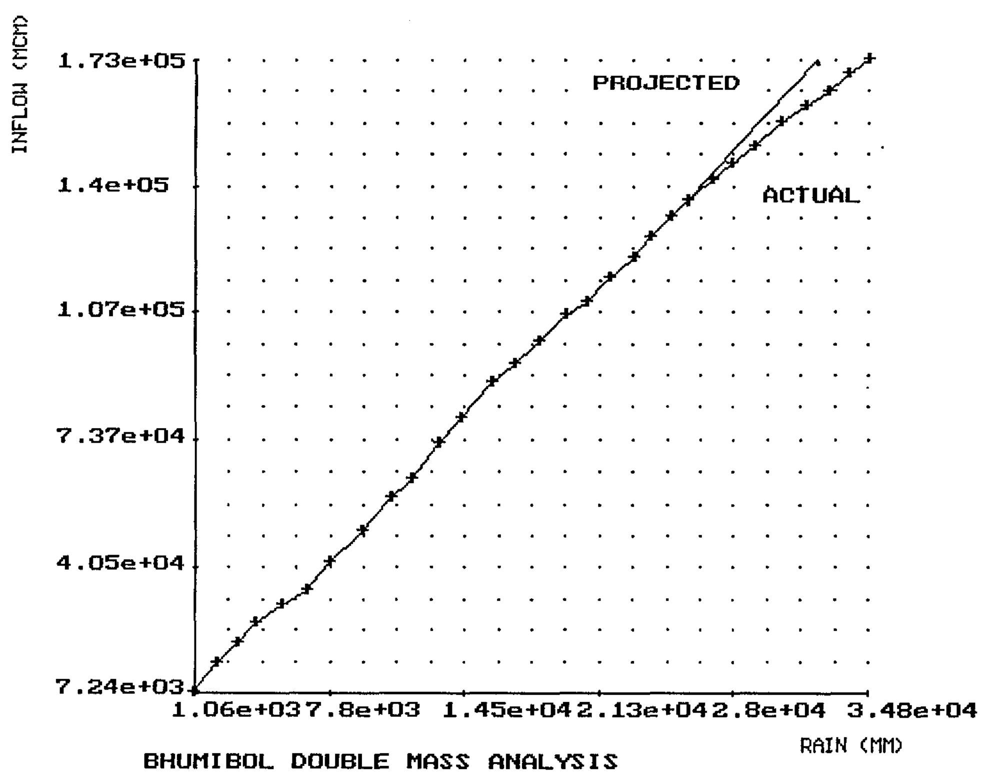

Figure F.4.3. - Double mass analysis of the Bhumibol reservoir system.

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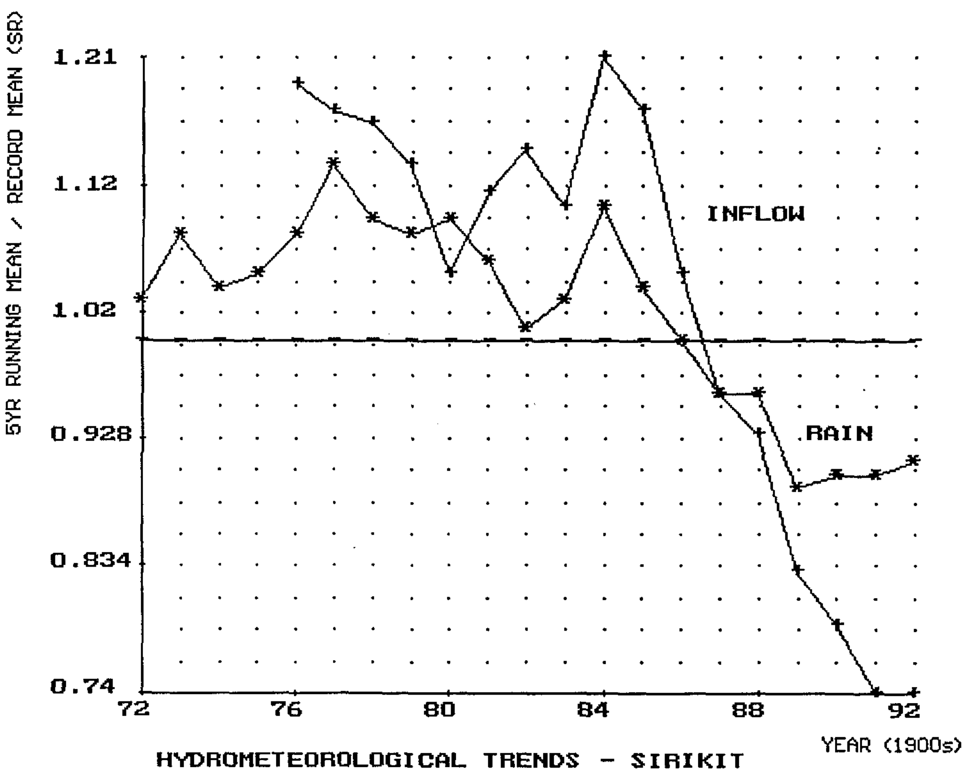

Figure F.4.4. - Hydrometeorological (rain and inflow) trends in the Sirikit reservoir system.

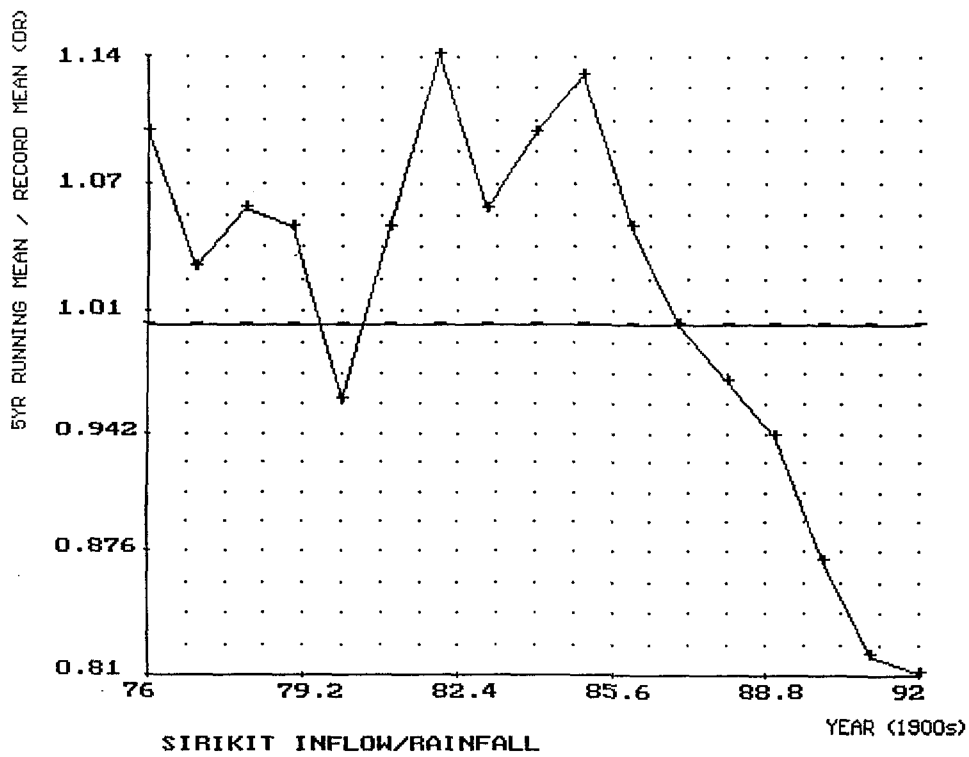

Figure F.4.5. - Normalized ratio of inflow to rainfall in the Sirikit reservoir system.

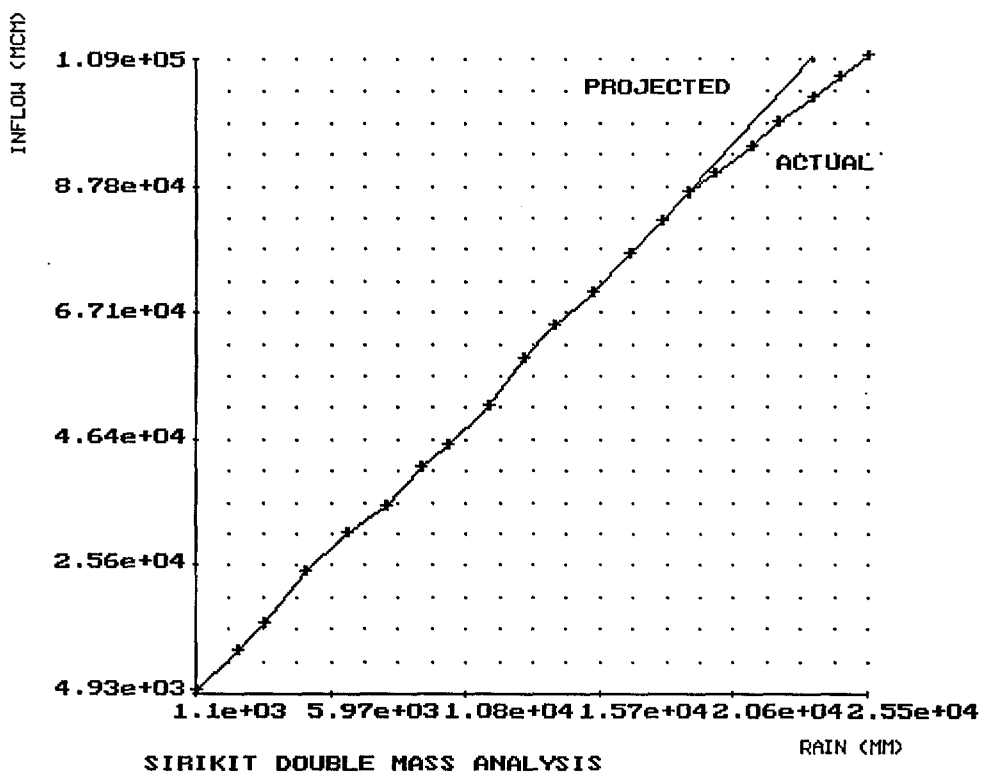

Figure F.4.6. - Double mass analysis of the Sirikit reservoir system.

3. Since about 1985, the percentage of rain falling in the Bhumibol and Sirikit catchment areas that reaches the reservoirs has steadily decreased. Apparently, some of the rain falling in the catchment areas is being captured or lost before it can reach the reservoirs.

4. The hydrological drought is not the result of natural rainfall deficiencies but, rather, a water management problem resulting from counter-productive, man-made activities in the Bhumibol and Sirikit catchment areas.

F.4.3.2 Recommendations

1. It is recommended that the RTG investigate the reasons why the percentage of rain reaching the Bhumibol and Sirikit reservoirs is steadily decreasing, and the implications for the water management of northern Thailand.

F.5. Hydrological Evaluation

The above information results in the conclusion that using historical hydrological records to conduct a conclusive, secondary, hydrological evaluation of the rainmaking demonstration project is not feasible. The change in relationship between rainfall and inflow in the Bhumibol reservoir system would make it difficult, if not possible, to attribute any future changes to seeding. Careful examination of figure F.4.3 indicates that changes in the inflow-rainfall relationship also occurred prior to 1984. The purpose of such a secondary hydrologic evaluation, which is still recommended, is to obtain support for the primary evaluation based on contemporary precipitation measurements.

6. References

EGAT (Electric Generating Authority of Thailand), 1989: *Introduction to EGAT's Hydro Power Development*, 36pp.

R-94-01

THAILAND APPLIED ATMOSPHERIC RESEARCH PROGRAM

Final Report
Volume 3

Demonstration Project Operations Plan

Submitted to
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Under
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March 1994

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Bureau of Reclamation
Denver Office
Research and Laboratory Services Division

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16. ABSTRACT

This final report, prepared by the Bureau of Reclamation under the PASA, consists of three volumes. Volume 1 includes a summary of the AARRP structure, the contributions to the AARRP by the U.S. and the Royal Thai Governments, and the institutional development, technology transfer, technical, and scientific accomplishments. Volume 1 concludes with a summary of problems encountered, lessons learned, and recommendations for the future. Volume 2 presents a detailed account of the scientific studies and their findings, and provides the design of the demonstration project (also known as AARRP Phase 2). Volume 3 presents the operations plan for the demonstration project.

Results of the AARRP cloud modeling and field studies suggest that increasing rainfall by static, warm cloud seeding with hygroscopic particles and by dynamic, cold cloud seeding with silver iodide are scientifically promising. A definitive warm and cold cloud seeding demonstration project to quantify the water augmentation potential of these rainmaking techniques in Thailand is warranted and recommended as the next logical AARRP activity. This PASA has provided a design and operations plan for the proposed demonstration project, as well as the equipment needed to carry it out. Training in the operation, maintenance, and use of this equipment for field experiments has also been provided; however, training in the scientific decisionmaking associated with the execution of the required seeding procedures was not completed, and training in the analysis, evaluation, and interpretation of experimental results was only started. As a result, Thai scientists are not yet capable of implementing the proposed demonstration project on their own. Therefore, it is recommended that the demonstration project be implemented *if and only if* the MOAC continues foreign technical assistance to 1) ensure that the demonstration project is carried out in strict accordance with the proposed design following international scientific standards, 2) complete the technology transfer and training started under the AARRP and provide the Thai scientists with a full capability to plan, conduct, monitor, and evaluate rainmaking projects, and 3) transfer the demonstration project seeding technology to Thailand's operational rainmaking program.

17. KEY WORDS AND DOCUMENT ANALYSIS

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b. IDENTIFIERS--

c. COSATI Field/Group 08B ***COWRR:*** 0802 ***SRIM:***

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THAILAND APPLIED ATMOSPHERIC RESOURCES RESEARCH PROGRAM

Final Report
Volume 3
Demonstration Project Operations Plan

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William L. Woodley
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Research and Laboratory Services Division
Denver Office
Denver, Colorado

March 1994

UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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DEDICATION

This report is dedicated to His Majesty King Bhumibol Adulyadej, who provides spiritual and scientific leadership for Thailand's program of rainmaking.

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ACKNOWLEDGEMENTS

Many individuals made the AARRP (Applied Atmospheric Resources Research Project) and this report possible, and we want to take a moment to acknowledge them.

We thank USAID/Thailand for their confidence in Reclamation to serve as their technical representative in the execution of the AARRP, and their support of Reclamation in carrying it out. We gratefully acknowledge the guidance and support of former Mission Director John R. Eriksson, under whose leadership the AARRP was conceived and launched, and current Mission Director Thomas H. Reese, III, under whose leadership the AARRP was successfully concluded. Thanks are also due to Mr. Douglas Clark, Mr. David Delgado, Mrs. Thongkorn Hiranraks, and Mr. Kamol Chantanumate, who successfully facilitated intergovernmental project matters and assisted in the resolution of project issues.

We thank Khun Sommai Surakul, Permanent Secretary of the MOAC (Ministry of Agriculture and Cooperatives) and AARRP Director, and Khun Saneh Warit, Director of the BRRAA (Bureau of Royal Rainmaking and Agricultural Aviation) and AARRP Manager, for their support and leadership in carrying out the AARRP. Years of painstaking work by Khun Sommai, Khun Saneh, and their staffs brought the program to where it is today.

A special thanks is due to Khun Metha Rajatapiti, former Director of the RRRDI (Royal Rainmaking Research Development Institute), and the RRRDI Advisory Board and its able Chairman, Dr. Debhanom Muangman, for their vision and dedicated efforts to upgrade Thailand's weather modification program. Their efforts contributed to establishment of the Weather Modification Assessment - Kingdom of Thailand, which, in turn, led to the establishment of the AARRP.

Thanks are also due to our Thai colleagues, who made us feel welcome in their beautiful and exotic country. We are especially grateful for the leadership of Mr. Warawut Khantiyanan, Assistant RRRDI Manager in charge of all AARRP activities, and Mr. Wathana Sukarnjanaset, AARRP Field Operations Director. The success of the AARRP effort to date is due in large measure to their guidance and hard work.

Several Thais scientists became actively involved in helping us with some of the analyses that are presented in this report. Their contributions will be duly recognized in the scientific papers that will be written about the results of the AARRP effort in the months ahead. In the interim, we thank the following persons for their assistance with various aspects of this Final Report:

Warawut Khantiyanan
Wathana Sukarnjanaset
Prinya Sudhikoses
Song Klinpratoom
Sommart Daengjai
Somchai Ruangsuttinarupap
Rachaneewan Talumassawatdi

Finally, we thank Thai Flying Service, specifically Col. Annek and Mr. Chatit, and the pilots of the Agricultural Aviation Section, MOAC, for meeting our needs and accommodating our requests in the conduct of the warm and cold cloud seeding experiments. This work was done in some cases under very difficult flight circumstances. Our thanks for a job well done.

GLOSSARY AND ACRONYMS

AARRP: Applied Atmospheric Resources Research Project.

ACRP: ASEAN Cooperative Rainmaking Project.

AgI: silver iodide.

a.g.l.: above ground level.

ASEAN: Association of Southeast Asian Nations.

ATT: Agricultural Technology Transfer Project.

BRRAA: Bureau of Royal Rainmaking and Agricultural Aviation.

Cb: cumulonimbus.

CCL: convective condensation level.

CCN: cloud condensation nucleus.

$CaCl_2$: calcium chloride.

Cold cumulus cloud: a large cumulus cloud whose top rises above the 0 °C level and in which precipitation development by ice particle growth processes is dominant. If the cloud top temperature reaches -10 °C to -25 °C, the cloud becomes suitable for glaciogenic seeding.

Convective cell: the basic element of convective cloud systems, consisting of a single updraft and down draft couplet. The convective cell has been selected as the treatment unit of the 1991 AARRP experiments.

DAS: data acquisition system.

DTEC: Department of Technical and Economic Cooperation.

"Dynamic Seeding": seeding whose primary purpose is to invigorate the internal circulations that sustain the cloud, force the ingestion and processing of more water vapor, leading to larger or more long-lived clouds and increased rainfall.

EEC: Enterprise Electronics Corporation.

EGAT: Electricity Generating Authority of Thailand.

Experimental unit: the convective elements, convective cells, and small multiple-cell convective systems within a circle having a radius of 25 kilometers and centered at the location of the convective cell that qualified the unit for treatment.

FACE: Florida Area Cumulus Experiment.

FOC: AARRP Field Operations Center at the RRFRC.

FOD: AARRP Field Operations Director.

GMS: geostationary meteorological satellite.

GMT: Greenwich mean time.

GPCM: Great Plains Cumulus Model.

GPS: global positioning system.

Glaciogenic seeding: seeding of a cloud with ice-forming chemicals to bring about the conversion of its supercooled water to ice.

IAS: indicated airspeed.

IRIS: Interactive Radar Information System.

"Metwatch": Frequent visual observations of cloud conditions over the AARRP study area, especially the development of convective clouds.

MCM: millions of cubic meters.

MLR: multiple linear regression.

MNR: maximum natural rainfall.

MOAC: Ministry of Agriculture and Cooperatives.

MRPP: multi-response permutation procedure.

m.s.l.: mean sea level.

NASA: National Aeronautics and Space Administration.

Non-operational day: a non-operational day is declared by the Field Operations Director when it is desired to give all AARRP personnel time off; generally, the declaration will be made the previous day.

"Nowcasting": a close meteorological surveillance of the project area to determine the weather conditions that already exist and those that are expected to exist in the next 2 hours.

Operational-go day: an operational-go day is declared by the Field Operations Director when convective cloud systems that are likely to be suitable for warm and/or cold cloud seeding exist in the study area, indicating that randomized cloud seeding experiments should commence as soon as possible.

Operational-standby day: an operational-standby day is declared by the Field Operations Director when conditions suitable for randomized seeding experiments do not exist in the study area now, but are expected to develop within the next 2 to 6 hours.

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Operational-stand down day: an operational-stand down day is declared by the Field Operations Director when it is desired to suspend operations for the high altitude aircraft crew and the rawinsonde team for the 1300 LST (local standard time) sounding; all other project activities should be continued.

PASA: participating agency service agreement.

PCWG: project coordinator working group.

PDF: probability density function.

PE: precipitation efficiency.

PRF: pulse repetition frequency.

Randomization: a process in experimentation whereby what is to be done to a treatment unit is determined randomly from a set of treatment decisions. Prior to experimentation, the treatment decisions are generated by a mathematical process that ensures that the assignment of treatment is truly random.

Randomized research day: a randomized research day for warm and/or cold cloud seeding is declared after aircraft penetrations of convective clouds establish that suitable conditions are present and that randomized seeding operations are about to begin.

Reclamation: Bureau of Reclamation.

RFC: Regional Forecast Center.

RRFRC: Royal Rainmaking Field Research Center at Chiang Mai Airport.

RRRDI: Royal Rainmaking Research Development Institute of the Kingdom of Thailand.

RSA: resident scientific advisor.

RTG: Royal Thai Government.

Small multiple-cell convective system: a radar echo containing two or more reflectivity maxima or cells, generally within a common echo boundary, but having no horizontal dimension greater than 100 kilometers.

"Static Seeding": seeding to increase rainfall by improving the precipitation efficiency of the cloud.

Study area: the area in northwest Thailand over which randomized seeding operations may be conducted. A map of this area is provided in the main portion of this report.

SLWC: supercooled liquid water content.

SMF: seeding multiplicative factor.

SWCP: the Southwest Cooperative Project that has been conducted in West Texas during portions of the summers of 1986, 1987, 1989, and 1990. This program is continuing.

TAS: true airspeed.

TCu: towering cumulus.

TRMDP: Thailand Rain Making Demonstration Project.

TRMM: Tropical Rainfall Measuring Mission.

TMD: Thai Meteorological Department.

Treatment: The result of the randomization scheme which determines what action is to be taken upon the experimental unit. The treatment will be either to seed convective cells within the experimental unit or to consider the experimental unit as a control and conduct simulated treatment.

Treatment unit: a convective cell within the experimental unit which meets the seeding criteria of liquid water content and updraft speed. The convective cell receives the treatment (actual or simulated) and is the cell in which any treatment effect should first be detected.

TWG: Technical Working Group of the AARRP.

USAID: U.S. Agency for International Development.

VOR/DME: very high frequency omni range/distance measuring equipment.

Warm Cloud: a cumulus cloud whose top never rises above the 0 °C level, and in which precipitation development by collision and coalescence processes is dominant.

WMO: World Meteorological Organization.

WWC: Woodley Weather Consultants.

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TABLES

FIGURES

1. INTRODUCTION

The rationale and design for the warm and cold cloud seeding demonstration project [AARRP (Applied Atmospheric Resources Research Program) Phase 2] appear in "Volume 2—Demonstration Project Design" of this Final Report. This document provides the operations plan for implementing the demonstration project.

The rainmaking demonstration project (AARRP Phase 2) will run from about April 15 through October 31 each year. The initial commencement date may change depending on the readiness of the AeroCommander 690B aircraft and Doppler weather radar system located near Omkoi, both of which are essential to the field experiments. The cold cloud seeding demonstration project will take place exclusively from April 15 through June 15. From June 16 through October 31, the warm cloud seeding demonstration project will have priority.

The main question to be addressed in AARRP Phase 2 is:

1. Can warm and cold cloud seeding produce more precipitation on the ground than would occur naturally, and how much of a precipitation increase can be produced?

A number of ancillary scientific questions will also be addressed. The answers to these questions will greatly strengthen the credibility and plausibility of the area-wide rainfall results. Among these ancillary questions are:

2. What is the effect of treatment on the scale of individual convective cells?

3. Do treated clouds grow larger and last longer following seeding?

4. How long do seeding effects last?

5. What physical processes account for the documented changes in precipitation?

6. What are the implications of the results of the demonstration project for water management in Thailand?

These questions should be answered during the course of the demonstration project. The success of the experiments will depend in part on hard work, cooperation, and communication among all participants. The projected experiments are a complex undertaking with a number of vital components, including: the weather forecasting effort, the aircraft/seeding program, the radar and rain gauge programs, the rawinsonde program, and the data management effort. If problems arise in any program component, the overall program will suffer.

The most serious challenge faced by all participants will be maintaining a high level of quality work despite adverse working conditions that include heat and humidity, frequent rains, and long working hours. It is hoped that this detailed operations plan will make the job of all participants a little easier. This plan will be no substitute, however, for the hard work and dedication that will be asked of everyone.

2. PARTICIPANTS AND RESPONSIBILITIES

The proposed demonstration project is a scientific undertaking of governmental agencies within the Kingdom of Thailand. The consulting professional services of a U.S. firm with knowledge and experience in dynamic cold seeding and static warm cloud seeding and experience with the AARRP is strongly recommended. Participants in the field project come from: the RRRDI (Royal Rainmaking Research and Development Institute) of the Kingdom of Thailand, the TMD (Thai Meteorological Department), Thai Flying Service, and the foreign consultants. A listing of each participant and his/her responsibility in the field experiments is provided below.

2.1 Executive/Administrative Personnel

Mr. Sommai Surakul - MOAC (Ministry of Agriculture and Cooperatives) Permanent Secretary, Chairman of the ATT Executive Committee, Chairman of the AARRP Steering Committee, and AARRP Director

Mr. Thana Tongtan - Director of MOAC Projects Division, AARRP Deputy Director

Mr. Saneh Warit - Director of the BRRAA, AARRP Manager

Mr. Prasert Kosalyawit - Head of BRRAA Administrative Section

Ms. Sukanya Sakaew - BRRAA Rainmaking Section, Director of RRRDI

Mr. Warawut Khantiyanan - Head of RRRDI Research Project division, AARRP Activities Manager

Mr. Wathana Sukarnjanaset - Head of RRRDI Data Base and Documentation Division

Mr. Prinya Sudikoses - Head of Atmospheric Survey Division

Mr. Preecha Bun-O-Pars - Head of RRRDI Instrumentation and Development Division

2.2 Participants Projected for the 1994 Field Season

Foreign Consulting Scientists. —

Foreign Expert No. 1 - To be determined

This foreign expert will oversee the collection of the radar data and take the lead role in the analysis of the volume-scan radar data and the development of the rainfall estimation technique using a combination of radar and rain gauge data. This person will provide analysis software for installation on the MicroVax system at RRRDI, and will provide training in the use of this software for the analysis of project data.

Foreign Expert No. 2 - To be determined

This foreign expert will consult with Thai scientists on their scientific analyses. This person will also assist with the conduct of the randomized seeding operations, especially those aspects related to the application of the cloud models and the warm cloud seeding experiments. This foreign expert will also assume the lead consulting role in the evaluation of the warm cloud experiments.

Foreign Expert No. 3 - To be determined

This foreign expert will assist with the conduct of the randomized seeding operations, especially those aspects related to aircraft cold cloud selection and seeding procedures. This person will participate in all flights, including preparation of a typewritten summary of each flight day in which he participated and put a copy of the summary in the daily file. This person will also assist in the processing of the aircraft data, and assist with the analysis and interpretation of the radar data obtained during the course of cold cloud seeding experiments.

AARRP Activities Manager. —

Khun Warawut Khantiyanan - AARRP Activities Manager

Khun Warawut is responsible for all AARRP activities. He will participate in RRRDI management planning for the AARRP and in the review and finalizing of the AARRP Field Operations Plan. During the field operations season, he will be based in Chiang Mai, but will spend time at the AARRP radar and other project sites. He will be responsible for ensuring that the AARRP Field Operations Plan is being followed, that all problems are dealt with in a timely manner, and that project personnel receive the training that is needed to perform their duties.

Field Operations Director. —

Khun Wathana Sukarnjanaset - Field Operations Director

The Field Operations Director is responsible for overseeing and managing the daily AARRP field operations to ensure that the program is proceeding as planned. The Field Operations Director is responsible for making key decisions in the conduct of daily operations and the launching of randomized seeding missions. He is also responsible for opening the envelope containing the randomized instruction. At the debriefing the following morning, he will seek input from other project scientists and assign preliminary warm and cold cloud seeding classifications for the day using radar, satellite, rawinsonde, aircraft, and visual cloud observations.

Khun Song Klinpratoom - Assistant Field Operations Director

The Assistant Field Operations Director will help the Field Operations Director in managing the program, especially in the area of equipment status. It is important that he receive daily reports on the status of each program component and that he instigate remedial action when problems arise. A daily record will be kept of the status of each piece of equipment.

Aircraft Team. —

The AARRP will have three scientists assigned to the aircraft team; however, only two at a time will fly on the high altitude AeroCommander 690B aircraft. During warm cloud seeding operations, one of these three scientists will fly on the CASA warm cloud seeding aircraft.

Khun Prinya Sudhikoses - Flight Meteorologist and Team Leader

Khun Prinya will normally direct the research flights and conduct debriefing activities in the absence of the foreign expert. He will oversee the reduction of the aircraft data with assistance from Khun Sommart and/or Khun Song. Khun Prinya will also ensure that the required data sets for each flight day are filed in the daily folder, including his typewritten assessment of the previous day's flight activity.

Khun Sommart Daengjai - Flight Scientist
Khun Song Klinpratoom - Flight Scientist

Either Khun Sommart or Khun Song will fly with Khun Prinya on research missions and be responsible for the following: providing aircraft expendables [i.e., floppy disks, video tapes, flight forms, AgI (silver iodide) flares], performing calibrations of all aircraft meteorological systems, serving as the liaison between RRRDI and Thai Flying Service personnel, and assisting with the reduction of the aircraft data.

Khun Anuchit Sisathittham - Aircraft Electronics Technician

Khun Anuchit will assist the aircraft team with their aircraft-related duties, use his electronics expertise to address problems with the aircraft meteorological instrumentation and data systems, and mount and dismount racks of AgI flares on the underbelly of the aircraft. He will keep a careful record of all flare expenditures and misfires and provide a post-flight report to the aircraft teams. A copy of the post-flight report is to go into the daily folder.

Khun Anupap Pavavathananusorn - Warm Cloud Seeding Chemical Load Master

Khun Anupap will be responsible for supervising the preparation of the warm cloud seeding chemicals and the loading of these chemicals onto the various warm cloud seeding aircraft. He will keep a careful record of all chemicals used and provide a post-flight report to the aircraft teams. A copy of the post-flight report is to go into the daily folder.

Others involved with aircraft and/or aircraft data: pilots and maintenance personnel from Thai Flying Service, and the foreign experts.

Radar Team. —

Khun Noppadol Boonyachalito - Chief of Radar Operations Team

As Chief of AARRP Radar Operations, Khun Noppadol's duties will include supervision of calibration, maintenance, and data checks; setting of schedules; and supervising personnel. Khun Noppadol (or a designated radar operator) will report the status of the radar to the Field Operations Director on a daily basis prior to the morning briefing. During randomized seeding operations, Khun Noppadol or his designee will communicate with the Field Operations Director or, if designated, directly with the flight scientist on the aircraft to advise him of the type and location of clouds that are developing in the project area and, in particular, clouds that may be hazardous to the project aircraft.

Khun Kitcha Sirithus - Assistant Chief, Radar Operations Team

Khun Kitcha will assist Khun Noppadol and serve as Acting Chief in his absence. His duties will include assisting with radar operations during periods of experimental studies.

Khun Kamol Siriburanapanont - Radar Technician/Operator
Khun Veeraphol Gawin - Radar Technician/Operator
Khun Chupong Poung Dok Mai - Radar Technician/Operator

The radar technicians/operators will work shifts to ensure that the AARRP radar system is operated 24 hours a day during the field season. They should all have the opportunity to work the day-time shift that includes the expected periods of experimental operations.

Engineer Team. —

Khun Warawoot Ninwiboon - Chief, Engineer Team

Khun Warawoot will be responsible for all AARRP equipment and instrumentation. His team will oversee the repair of equipment, schedule preventive maintenance, and ensure that all project instrumentation is properly calibrated. Primary areas of responsibility include radar calibration and maintenance, the instrumentation and data acquisition system on the AeroCommander 690B high altitude aircraft, and the AARRP communication network.

Khun Anuchit Sisathittham - Electronics Technician
Khun Nin Intararochana - Electronics Technician

The electronics technicians on the Engineer Team will assist in equipment installations, calibrations, preventive maintenance, and in the repairing of equipment and instrumentation.

Rain Gauge Team. —

Khun Noppadol Anukul - Chief, Rain Gauge Team

Khun Noppadol will serve as the chief rain gauge technician. He will be responsible for routinely servicing the rain gauge network and rain gauge maintenance, calibration, and repair. The rain gauge team should service all of the rain gauges and collect the recorded data on a monthly basis. The data cartridges should be downloaded using GEMS as soon as possible after they are collected. The downloaded data should be checked against the servicing logs for possible gauge malfunctions. Problems should be brought to the immediate attention of the Field Operations Director. Diskettes containing the recorded rainfall data and copies of the rain gauge servicing logs will be transported to the FOC (Field Operations Center) in Chiang Mai for further data quality control and processing.

Khun Somporn Chotikul - Assistant Rain Gauge Technician

Khun Somporn will assist in the servicing and operation of the project's rain gauge network.

Rawinsonde Team. —

Khun Mongkut Shuva - Chiang Mai Rawinsonde Technician/Operator

Khun Mongkut will be in charge of the daily collecting of atmospheric soundings at the TMD's Chiang Mai Regional Forecast Center. The TMD's 0700 LST (0000 GMT) sounding will be processed for project use. He will make additional project soundings, using the TMD's equipment, as requested by the Operations Director. It will be his responsibility to code the raw Chiang Mai upper air sounding and process it through the PJRAOB program, or use the TMD's WMO (World Meteorological Organization) format sounding, as input to other SONDE program modules, including ANALYZR, SKEWT, and GPCM (Great Plains Cumulus Model).

Khun Kitti Toopsri - Radar Site Rawinsonde Technician/Operator
Khun Boonrod Yamsomchit - Assistant Rawinsonde Technician

Khun Kitti will use the AARRP rawinsonde system located at the radar site to collect upper air sounding data during operational days with randomized seeding operations. (A 0700 LST sounding is desired on all operational days; a second sounding at 1300 LST may be requested by the Operations Director.) He will also code the sounding data into the format required by SONDE program module PJRAOB and send the data file via fax to the FOC in Chiang Mai for further SONDE program processing.

Forecasting Team. —

TMD Staff Forecasters at Chiang Mai RFC (Regional Forecast Center)
Khun Wathana Sukarnjanaset - Field Operations Director
Khun Somchai Ruangsuttinarupap - Meteorological Technician
Khun Song Klinpratoom

The area weather forecasts will be prepared and provided to the AARRP by the experienced Thai forecasters working at the TMD's Chiang Mai RFC. The on-duty AARRP Operations Director (usually Khun Wathana) will meet with the TMD forecaster to discuss the weather outlook for the day. The Operations Director will then give the weather forecast at the daily briefing for the AARRP operations. The AARRP forecast team personnel will be responsible for collecting and filing daily weather data from the TMD for use in post-evaluations of project operations.

Satellite Team. —

Khun Somchai Ruangsuttinarupap - Satellite Technician

Khun Wichai Khumsawat - Assistant Satellite Technician

The satellite team will prepare a satellite cloud report for the morning briefing and provide updates on cloud development and patterns on days with randomized cloud seeding operations. This report should be faxed from the Omkoi radar site to the FOC in Chiang Mai. Following the morning briefing, Khun Somchai and/or Wichai will monitor the satellite and radar data to determine when and where cloud conditions are approaching suitable status, and will keep the on-duty Operations Director informed about the current weather status and expected changes. Khun Somchai will be responsible for satellite data collection, quality control, and inventory.

Data Management Team. —

Khun Wathana Sukarnjanaset - Chief, AARRP Data Management Team and AARRP Data Manager

Khun Wathana will serve as Chief of the Data Management Team, with the overall responsibility for the collection and processing of all data needed for the evaluation of cloud seeding effects. He will also serve as the Data Manager for the AARRP. His Field Operations Director's responsibilities and duties will prevent him from performing the field data management tasks himself. However, he must have a good understanding of the tasks required, and must be a good manager in overseeing data technicians in accomplishing these tasks. Most of the data management work will probably be done at the FOC in Chiang Mai during the AARRP field season.

Khun Suklao Dokmai - Data Technician
Khun Vararat Thonglueng - Data Technician
Khun Janya Kochrit - Data Technician
Khun Penrat Ratchatavej - Data Technician

The Data Technicians working at the FOC will be responsible for the computer entry of project data as required, including the upper air sounding data from Chiang Mai and the AARRP Radar site. They will also monitor the flow of data and ensure that a complete data inventory list accompanies all project data shipments. If the status report on a particular system and/or actual data are missing from the daily file folder, they will take the action necessary to correct the deficiency.

Khun Boonrueng Thangtrongsakol - AARRP Data Archivist

Khun Boonrueng will serve the AARRP out of RRRDI in Bangkok by collecting and providing all non-project data, especially rainfall and upper air sounding data from the TMD. She will also inventory and store AARRP data shipments received from the FOC in Chiang Mai, make 8-millimeter tape copies of the original AARRP radar data tapes, make a list of the copied radar data tapes, and mail the tape copies with a list of the tapes to NASA (National Aeronautics and Space Administration).

Khun Rachaneewan Talumassawatdi - RRRDI Vax and PC Software Manager

Khun Rachaneewan will be responsible for all software for the Vax and PC computers, including the loading and updating of all software. She will also assist with the analysis of project radar and rainfall data on the MicroVax system at RRRDI.

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3. RESOURCES

Carrying out and evaluating these experiments will involve the following equipment and facilities:

1. An AeroCommander 690B cloud physics/seeder aircraft, which has the capability of flying for least 3 hours at 21,000 feet, measuring air temperature and dew point, SLWC (supercooled liquid water content), and cloud drafts, and ejecting up to 200 20-gram AgI flares during each flight. The aircraft also has a precise system of navigation, which records aircraft position so that the seeding positions can be known reliably to within 100 meters. The AeroCommander 690B aircraft has been provided for the AARRP effort under a Royal Thai Government lease with Thai Flying Service.

2. Two CASA aircraft, provided to the AARRP by the MOAC's Agricultural Aviation Division for use as warm cloud seeding aircraft. The two CASA aircraft have been equipped with a GPS navigation system to accurately document the positions and flight tracks of the aircraft during seeding operations. All of the warm cloud seeding aircraft have ports through which the warm cloud seeding chemicals can be dispensed.

3. A digitized S-band (10-centimeter) Doppler weather radar at the Omkoi radar site for collecting volume scan data of the development of rain within convective clouds, for providing real-time data for guiding experimental operations, and recording data for subsequent evaluation of the experiment. A remote radar scope has been installed at the Chiang Mai FOC for use in the meteorological surveillance of the project area.

4. A network of tipping bucket recording rain gauges to assist with the evaluation of the experiment in conjunction with the radar.

5. Two atmospheric sounding systems (plus the TMD system at Chiang Mai) to collect upper air data to be used as input to SONDE program modules to assess the suitability of a day for randomized cold and warm cloud seeding, and for later use in evaluating the experiments. One of the RRRDI systems will be located at the FOC in Chiang Mai to serve as a backup for the TMD system. The second project system will be used to make special upper air soundings from the AARRP radar site near Omkoi on days when randomized seeding operations are being conducted in the vicinity.

6. A satellite data receiving station, which has been installed in Omkoi to collect satellite data needed for daily meteorological surveillance of the project area, and subsequent evaluation of the operational days.

7. Selected weather maps, surface weather observations, radar observations, regional weather forecasts, and daily rainfall data obtained from the TMD's RFC in Chiang Mai, to be used in forecasting project randomized seeding conditions, and as input to a subsequent evaluation that makes use of predictor and covariate variables.

8. A VHF/FM radio system, to provide for voice communications between project sites, project aircraft, and project vehicles. Recently, a VHF repeater was installed to improve voice communications between the project radar site near Omkoi and the FOC in Chiang Mai; this repeater also allows telephone calls to be made from the

radio system. A UHF radio high speed data link has also been installed between the radar site and the FOC in Chiang Mai; this link allows the transmission of data via two microcomputers with modems.

9. A VHS camcorder and a multi-system video cassette player to allow video records of cloud development to be made from selected sites, primarily the radar site, and subsequently to be reviewed as part of the project evaluation.

10. Tracking software to be used with the analysis of the radar observations to identify and track the convective cells, and to calculate their properties (height, reflectivities, area, durations, rain volumes, etc.)

11. Rainfall data processing and analysis software to correct errors in the original data, to reformat the data for subsequent analyses, and to analyze the processed data.

4. OVERVIEW OF THE DESIGN OF THE DEMONSTRATION PROJECT

The demonstration project will be conducted within the confines of the AARRP study area shown on figure 4.1, as dictated by cloud conditions and logistical considerations. Under only special circumstances should experimentation be carried out beyond these boundaries. No cold cloud seeding shall be conducted within 25 kilometers of the radar site at Omkoi. Although the radar can see echoes on its base scan within this 25-kilometer region, it will not be able to see the tops of echoes above about 12 kilometers (40,000 feet) a.g.l. (above ground level). This limitation occurs because the top of the radar volume scan is terminated at 27° (height of cloud = horizontal distance to cloud times the tangent of the angle to cloud top; tan 27° = 0.51). Likewise, no warm cloud seeding shall be conducted within 12.5 kilometers of the radar site; this limitation restricts the maximum echo tops the radar can see at the 12.5-kilometer range to about 6 kilometers (20,000 feet) a.g.l.

The randomized seeding instructions for both the warm and cold cloud experiments will be prepared by statisticians associated with the AARRP effort after consultation with the foreign consulting scientists. Separate sets of envelopes will be prepared for the cold cloud seeding demonstration project (two sets) and the warm cloud seeding demonstration project (two sets). The card within each decision envelope for the cold cloud seeding experiment will say either "Seed" or "No Seed," and the flight scientist will act accordingly within the chosen experimental unit. The card within each decision envelope for the warm cloud seeding experiment, which has a "crossover" design, will specify whether the north target area of the target pair will be seeded or not seeded. If the decision is not to seed the north target area, the south target area will be seeded. In preparing the instructions, care will be exercised to avoid long runs of the same treatment decision.

The CORE of the cold cloud experiment for Phase 2 of the AARRP Experiments will be, as before, randomized "on-top" seeding of cold clouds using a glaciogenic seeding agent, i.e. AgI at temperatures ranging from -6 °C to -12 °C. The experimental unit consists of the convective elements, convective cells, and small multiple-cell convective systems, receiving real (i.e., AgI flares) or simulated treatment, within a circle having a radius of 25 kilometers and centered at the location of the convective cell which qualified for the first treatment. The treatment units are the convective towers that correspond to the convective cells within the experimental unit and that meet the SLWC and updraft seeding criteria. The cell will receive the treatment, and any effect of seeding should be manifested first in the treatment unit (the cell), and later in the overall experimental unit. The treated regions will correspond to convective cells that can be identified on radar as regions of reflectivity maxima that are embedded within an overall area of showery precipitation. Radar and rain gauge estimates of precipitation will be used to evaluate the demonstration project.

The selection and termination of the experimental unit will be based upon the following requirements:

1. A preliminary sampling pass shall establish that convective cells in the area contain maximum (1-second values) liquid water contents of at least 1.0 gram per cubic meter and maximum (1-second values) updrafts of at least 1,000 feet per minute (i.e., ≥ 5 meters per second), as determined from real-time readouts aboard the aircraft.

2. No cloud or cell within the experimental unit at the time of initial treatment shall have a top reaching above 10 kilometers a.g.l.

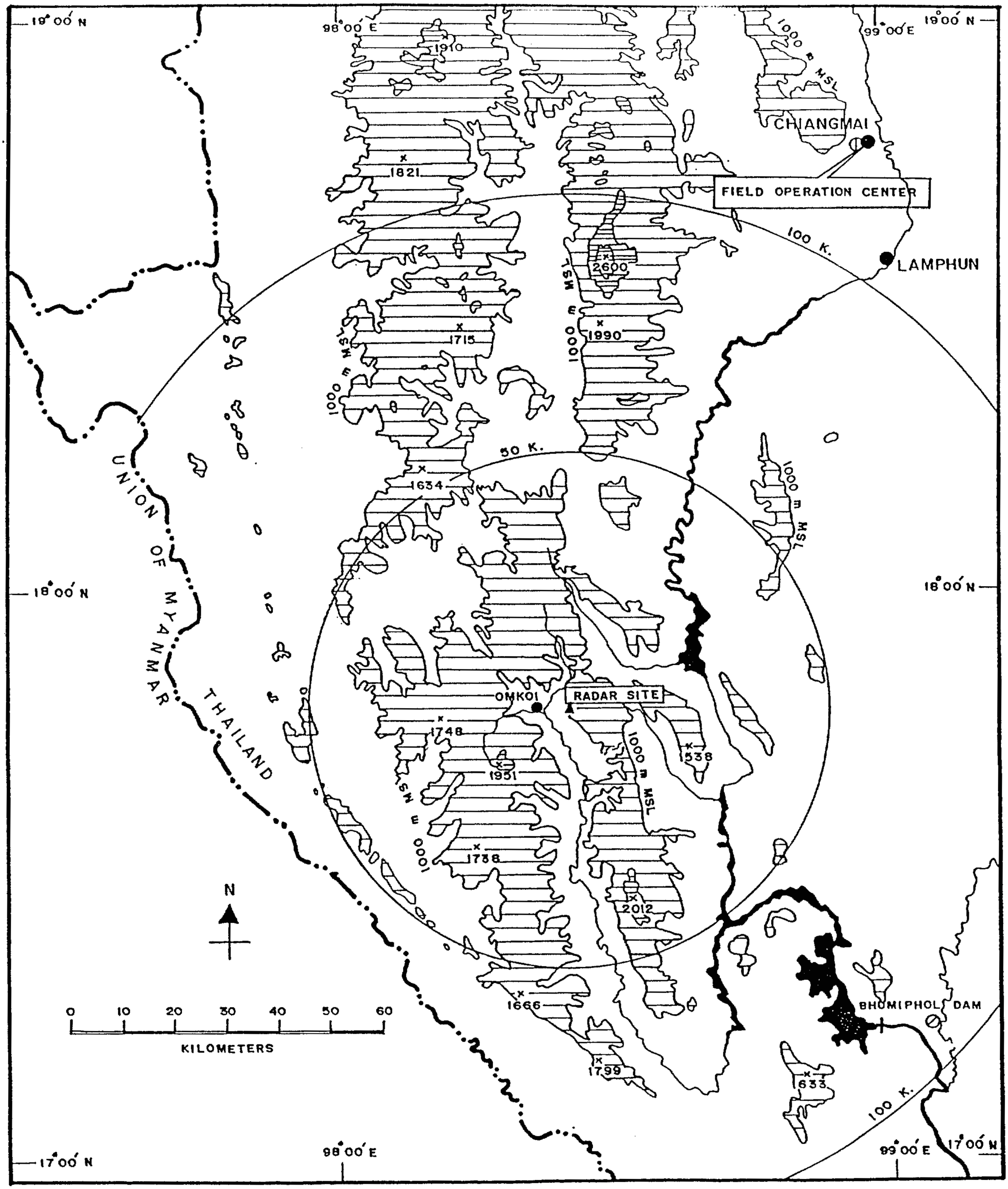

Figure 4.1. - Project area for the AARRP Phase 2.

3. At least some of the subject cells shall have top temperatures of -10 °C or colder.

4. At the time of selection, the center of the prospective experimental unit shall be located at least 40 kilometers from cumulonimbus clouds displaying radar reflectivities of 50 dBZ or greater in the vicinity.

5. Treatment of clouds within the experimental unit is to be terminated if: a) more than 1 hour has elapsed since the last seeding *and* if there are no longer any echoes contained within its boundaries, and/or if b) the center of the experimental unit moves beyond 159 kilometers from the radar, and/or if c) the monitoring S-band radar has had an operational failure.

The CORE of the warm cloud experiment for Phase 2 of the AARRP effort is randomization by area, and then seeding the clouds within the randomly selected area using the $CaCl_2$ (calcium chloride) particles. The warm cloud experimental unit consists of the convective elements, convective cells, and small multiple-cell convective systems receiving real or simulated treatment. The treatment units are the convective cells within the experimental unit that meet the seeding criteria. Seeding will be done as low in the clouds as safety and logistical considerations permit, but no higher than 100 meters below cloud top.

Although it may be desirable to have no radar echoes within either of the two areas before declaring a warm cloud experimental unit, this qualification criterion will not be used for the Phase 2 effort, which will allow the scientist on board the AeroCommander high altitude aircraft to make the experimental unit declaration based on observed/measured cloud depths. However, analysts will post-stratify the data according to criteria provided in the design of the project ("Volume 2—Demonstration Project Design").

5. SCHEDULE OF ACTIVITIES ON OPERATIONAL DAYS

During the field season period, *all days will be considered operational for the demonstration project unless declared non-operational the previous day by the AARRP Field Operations Director* for one of the following reasons: (1) the high altitude research aircraft or warm cloud seeding aircraft (warm cloud experiment only) or the radar is inoperative; (2) the high altitude aircraft or warm cloud seeding aircraft (warm cloud experiment only) is not available because of scheduled routine inspections or maintenance; (3) the ground to air communications are inoperative; (4) project personnel have been working long days and need rest; or (5) project personnel have been given time off to observe a Thai national holiday.

Although every operational day during a randomized seeding experiment differs, some activities must be performed each day. The activities common to each operational day, and the approximate local Thailand times when they should be performed, are listed below.

Time	Activity
0700	*Make 0000 GMT upper air soundings* - TMD technicians at the Chiang Mai RFC will make the synoptic time sounding. AARRP technicians at the radar site should also make a 0000 GMT upper air sounding.
0730	*Code radar site sounding data* - Technicians code the sounding data in the format required for SONDE program module PJRAOB; PC data file is sent via fax to the FOC in Chiang Mai for SONDE program processing. To run ANALYZR, radar site surface temperatures from the previous day must also be provided to the FOC.
0800	*Process Chiang Mai and radar site soundings* - AARRP rawinsonde team at the Chiang Mai FOC uses SONDE program modules to process and analyze sounding data from both sites; Operations Director checks SKEWT plots and data for possible errors.
0800	*Begin meteorological surveillance* - Unless the day has been declared "stand down," the satellite and radar teams should begin a continuous weather watch with respect to convective cloud and rain development within the study area. The Operations Director should be kept informed of any significant changes so that flight operations can be adjusted accordingly.
0815	*Operations debriefing* - An operations debriefing will be held at the FOC if the AeroCommander aircraft flew a project mission the previous day. The purpose of the debriefing is to assess the previous day's operations and to address any problems that may have arisen. A preliminary classification of the *previous* day will be given based upon observed conditions.
0900	*Satellite cloud report* - Satellite team at the Omkoi radar site faxes cloud report to FOC.
0900	*Weather and status reports* - Current weather observations and/or equipment status reports are received at the FOC from the AARRP radar, the AeroCommander crew, the CASA crew, and the TMD staff.

0915 *TMD weather forecast* - Operations Director and Aircraft team attend weather briefing held by TMD staff forecaster at the Chiang Mai RFC.

0930 *Project operations briefing* - Operations Director leads briefing for all available project staff at the FOC; items covered include:

a) equipment status
b) personnel status
c) current weather (radar, satellite, etc.)
d) weather forecast
e) seeding potential
f) preliminary experimental day declaration
g) operational status
- operational-go
- operational-standby
- stand down

1300 *Experimental day declaration update* - Operations Director can change the preliminary experimental day declaration made at the morning briefing based upon observed cloud conditions. That is, the afternoon can be changed from "cold cloud experiment" to "warm cloud experiment" (or vice versa), depending upon current convective cloud observations over the study area. This change is possible only in the period June 16 through October 31 in the rare circumstance that a cold cloud experiment is declared.

1300 *Make 0600 GMT upper air sounding* - Whenever the status is either "operational-go" or "operational-standby," the rawinsonde team will make a 0600 GMT sounding at either the TMD's Chiang Mai RFC or the AARRP's radar site near Omkoi. A second upper air sounding from the radar site is preferred; however, the Operations Director can request a sounding from Chiang Mai instead.

1400 *Process 0600 GMT sounding* - If a 0600 GMT sounding was made, the rawinsonde team uses SONDE program modules to process and analyze the sounding data; the Operations Director checks SKEWT plot and listed data for possible errors.

1600 *Project status update* - If project aircraft have not yet departed or are not preparing to depart for a randomized seeding experiment mission, the Operations Director can change the operational status to "stand down."

1700 *Process aircraft data* - Whenever the project aircraft have flown a mission, the aircraft team should process and summarize the collected data as soon as possible; this procedure includes completing all of the forms and preparing a written summary.

1800 *End of operation day* - This time can vary, depending upon the time of the return of project aircraft from experimental seeding missions.

6. PRELIMINARY EXPERIMENTAL DAY DECLARATION

The preliminary objective technique developed for forecasting convective cloud-top heights in Thailand is discussed in appendix C of "Volume 2—Demonstration Project Design." For the 54-day sample used in this study, 95 percent of the days had radar echo top heights greater than about 8.0 kilometers; consequently, the MLR (multiple linear regression) analysis equation derived from this sample cannot be used for selecting days with only warm convective clouds. Even with a much larger data set sample, it is believed that using the 95-percentile radar echo tops would not result in an objective technique that could be used operationally to make reliable warm or cold cloud seeding experimental day declarations.

Because of the difficulty in making preliminary warm or cold cloud seeding experimental day declarations, the field season has been separated into two subperiods based upon past experience gained during past experimental studies. The period from April 15 through June 15 will be devoted to the cold cloud seeding experiment; no warm cloud seeding experiments will take place during this period. The period from June 16 through October 31 will be devoted to the warm cloud seeding experiment.

The rawinsonde technician processing the 0700 LST (0000 GMT) Chiang Mai upper-air sounding will give the computer analyses produced by ANALYZR to the operations director by 0900 LST. The revised 1994 version of ANALYZR will provide predicted 95-percentile radar echo top heights over the two eastern target areas during the afternoon. The Predict value from ANALYZR should be between 7 and 11 kilometers, and should provide the operations director with a better indication of the convective cloud intensity to expect. Note that the revised ANALYZR program requires the input of the 2-kilometer updraft radius estimated natural cloud top from GPCM; therefore, GPCM must be run before ANALYZR.

Based on this sounding analysis, current weather condition, and status reports, the operations director will make his experimental day declaration at the end of the morning briefing, i.e., by 1000 LST. The fact that the 54-day sample used in the study had cold echo tops suggests that convective cloud development should be expected over the eastern AARRP target areas nearly every day. The operations director should provide his good, moderate, or poor forecast at the morning briefing, but the seeding experiments should not stand down based on this forecast. This decision should be made during subsequent nowcasting for the study area based upon actual observations.

The radar echo top prediction and all of the sounding variables from ANALYZR that were used in the preliminary study should be compiled on a daily basis. This data set should be used during the post-field season period to continue this study according to the recommendations listed in appendix C of "Volume 2—Demonstration Project Design." Using only good quality Chiang Mai sounding data in this study is very important if a better objective technique is to be achieved.

7. PREPARATIONS FOR RANDOMIZED SEEDING EXPERIMENTS

At the conclusion of the morning operations briefing, i.e., by 1000 LST, the Operations Director will *announce the operational status decision and the preliminary experimental day declaration*. All field project personnel at all field sites will be notified accordingly.

If the status is "operational-go," flight personnel will prepare for flight. Preparation for cold cloud seeding missions will include loading the AgI flares into the racks for mounting on the underbelly of the AeroCommander aircraft. Preparation for warm cloud seeding missions will include loading bags of hygroscopic chemical $CaCl_2$ particles on the warm cloud seeding aircraft. The Pilots will file a flight plan in accordance with standard procedures in Thailand. The AeroCommander aircraft mission will be launched immediately upon the arrival of the Aircraft Flight Scientists at the Chiang Mai Airport aircraft operations center. If the status is "operational-go" for a warm cloud seeding mission, the warm cloud seeding aircraft should take off from Chiang Mai shortly after the AeroCommander.

If the status is "operational-standby," all air crew personnel should be at their duty stations at the time prescribed by the Operations Director at the morning briefing. The Operations Director will monitor the radar and satellite displays and coordinate with the Satellite Data Analyst on the weather situation. The Aircraft Flight Scientists and Pilots should wait at the aircraft for notification by the Operations Director as to the time that the aircraft mission should be launched.

After the decision has been made to fly, the AeroCommander high altitude aircraft will take about 20 to 40 minutes to reach its operating altitude (normally 21,500 feet m.s.l. for cold cloud seeding and 8,000 to 15,000 feet m.s.l. for warm cloud seeding observation), and/or the warm cloud seeding aircraft reach their seeding altitude over the target area (normally 8,000 to 10,000 feet m.s.l.).

During the aircraft mission, the Satellite Data Analyst should continue to monitor and interpret all weather data sources with respect to cloud and rainfall development in the study area. The radar and satellite displays will be particularly helpful in this regard. He should keep the Operations Director informed of any significant changes so that flight operations can be adjusted accordingly.

8. THE COLD CLOUD EXPERIMENT

8.1 Introduction

The purpose of the cold cloud seeding aircraft missions is to conduct randomized seeding operations on convective cells contained within an experimental unit. The seeding of each cell is done by dropping flares of AgI into the updrafts of cold mixed-phase clouds. The identification of suitable cold clouds for seeding requires real time monitoring of cloud temperature, updraft velocity, and liquid water content. *Only the high altitude AeroCommander 690B aircraft is used in the cold cloud experiments of Phase 2.*

The AeroCommander 690B is a turbo-prop aircraft equipped with an airborne DAS (Data Acquisition System). In addition to standard avionics and flight instrumentation, the AeroCommander is equipped with the following airborne cloud seeding support instrumentation: a Johnson-William liquid water content meter, a thermo-electric dew point hygrometer, a reverse flow thermometer, a Ball variometer, and a satellite-based navigation GPS (Global Positioning System) that permits determination of the location of the aircraft to within 100 meters. The GPS is a major addition to the standard aircraft VOR/DME (very high frequency omni range/distance measuring equipment) navigation system because of its increased position accuracies. A forward-looking nose video camera has been mounted in the cockpit and provides a continuous view of cloud conditions during flight through the extreme right side of the windshield. Finally, the aircraft is equipped to eject 200 20-gram AgI flares that are loaded into racks, which are mounted on the underbelly of the aircraft forward of its tail.

Conducting the randomized cold cloud seeding missions is more complicated than it first appears. The first crucial decision point is the time to launch the AeroCommander aircraft. A normal fuel load will give about 3 hours aloft at 21,500 feet. A premature takeoff may mean that the fuel will run out before an experimental unit can be selected and treated. A late takeoff may mean that no suitable cold clouds will be found, because most of them have grown into large, mature, Cb (cumulonimbus) masses. The presence of TCu (towering cumuli) in the project area and a scattering of very small echoes are usually good indicators that it is time to be in the air. All things considered, it is better to be too early into the study area than too late.

8.2 Before Starting the Engines

Several items must be addressed before the AeroCommander aircraft engines are started. First, the Flight Scientists should check the time with a reliable source. Second, they must make certain that the hot-wire, liquid-water, sensing head is mounted on the aircraft. (The entire system should be calibrated at least once weekly, and some extra preparation time will be necessary on days when a calibration is planned.) Third, the Flight Scientists should make certain that they have the following with them before entering the aircraft and closing the door: two formatted floppy disks, two VHS video tapes, relevant forms, notebook, pen, pencil, and clipboard.

Once on board the aircraft, complete the preflight checklist before power is applied to the DAS. Make certain that the DAS switches are set as shown in the checklist. The checklist in the plastic page protectors in the flight notebook should always be used for this purpose.

8.3 After Starting the Engines

After the preflight checklist completion and engine start, power to the DAS should be requested and the next portion of the checking procedure should begin. In activating the DAS, make certain to check the date and time against the standard. Enter corrected values at the keyboard if necessary. Make certain that the *lens cap has been removed* from the video camera. The video tape should be inserted into the recorder and taping (both voice and video) should begin. If the tape has been used to video tape more than one day, great care must be exercised to ensure that the current taping begins *at the end* of the taping for the previous day. Otherwise, valuable previous data will be lost (i.e., recorded over).

During the climb to seeding altitude, while the aircraft sounding is being made (by activating event toggle No. 1), the Flight Scientist directing the flight should watch the convective cloud developments and form a mental picture of where the clouds are, their estimated depths, how they are organized, and how rapidly they appear to be growing. The initial contact with the Operations Director at the Chiang Mai FOC should be made at this time, to receive a briefing on the distribution of evolving clouds as seen on the remote radar display and the satellite workstation. The Operations Director may be in a better position to see the development of precipitating clouds and this additional target information may prove to be quite helpful.

All communications between the aircraft and either the Operations Director in Chiang Mai or the Radar Operator at the AARRP radar site near Omkoi are to be made on FM frequency 155.825 megahertz. Communications between the AeroCommander Pilots and the Thai air traffic control center, and also the Royal Thai Air Force radar at Doi Ithanon, are to be made on the assigned VHF frequencies.

The hot-wire, liquid-water sensor should be activated during the climb along with the heat switches for the pitot tube and the liquid water sensor. The aircraft should be ready for cloud penetrations as soon as it reaches the desired altitude, usually about 21,500 feet for temperatures between -8 °C and -10 °C.

8.4 In the Experimental Area at Seeding Altitude

Once in the experimental area at seeding altitude and temperature, the task is to identify where the cumuli are most likely to become suitable. The existing cloud field will give some hints. It is best to stay away from large Cb masses. The Flight Scientist should always be watching for large Cbs and should direct the aircraft away from them. Radar echoes on the Aircraft's radar can help in identifying Cb masses. In addition, both the Operations Director and the Radar Operator should watch for the development of radar echoes with high reflectivities and/or high tops within the study area. *If either of them observes intense radar echoes (> 50 dBZ) or echo tops greater than 10 kilometers a.g.l. within the study area, the Flight Scientist should be informed immediately.*

It is important to avoid a frenetic chase mode all over the study area. A good-looking seeding candidate as little as 50 kilometers away will not be suitable by the time the aircraft arrives at its location. Frequently, gentle orbits by the aircraft will be helpful in assessing the cloud conditions. A cloud mass can be viewed on one orbit and its change noted the next time around, perhaps 3 to 5 minutes later. Flying in circles for a time might be viewed as indecisive flight behavior by some, but such a procedure is better than playing the frustrating game of "chase the cloud."

While looking for the "perfect" cloud for qualification, the time should be used to complete the instrument status report form (fig. 8.1), the cloud penetration form (fig. 8.2) after each cloud pass, and the assessment of the weather form (fig. 8.3) prior to requesting a treatment decision. Copies of these forms should be on the aircraft at all times. A pencil should be used when filling out these forms so that any errors can be corrected. Although this task is always an annoyance to the Flight Scientist, the completed forms are very valuable during the later analysis phase.

8.5 Qualification of an Experimental Unit

The cold cloud experimental unit shall have the following characteristics before a randomized seeding instruction is requested from the Operations Director:

1. A preliminary sampling pass has established that convective cells within the prospective unit have SLWCs of at least 1.0 gram per cubic meter and updrafts at least 1000 feet per minute. All sampling pass measurements are to be made at ambient temperatures between -8 °C and -10 °C.

2. At least one cloud has a top temperature < -10 °C, and a number of hard supercooled cloud towers are available for seeding within the prospective unit.

3. No cloud or cell within the experimental unit at the time of initial treatment shall have a top reaching above 10 kilometers a.g.l.

4. At least some of the subject cells shall have top temperatures of -10 °C or colder.

5. At the time of selection, the center of the prospective experimental unit shall be located at least 40 kilometers from cumulonimbus clouds displaying radar reflectivities of 50 dBZ or greater in the vicinity.

6. The center of the prospective unit is at least 1/2 hour upwind (using 700-millibar wind) of the 25-kilometer radar dead zone, which is centered on the AARRP radar site.

7. The center of the prospective unit is within the 125-kilometer range of the AARRP radar.

During all penetrations, the Pilots are must fly the aircraft at a constant attitude so the Ball Variometer will give an accurate indication of cloud drafts. The Flight Scientist is reminded to mark the entry point of each pass with the cloud pointer *until a cloud that meets the qualification criteria has been found.* This position will give the center of the experimental unit, and the Flight Scientist can use this reference to make certain that he does no seeding or simulated seeding more than 25 kilometers (about 13 nautical miles) from this point.

The center position of the unit should be updated every 30 minutes by the radar operator, who is responsible for moving the center on the radar screen based on the motion evident in echoes within and nearby the experimental unit. If the unit has moved appreciably, the aircraft cloud pointer can be updated by flying to the new position and resetting the pointer. If this update is not feasible, the unit position can be entered directly into the GPS navigation system and the aircraft can be navigated relative to that point using GPS.

Timing is everything in conducting airborne seeding operations. If a particular tower is penetrated when it is young and growing, it likely will have a strong updraft and copious quantities of SLWC. However, as little as 5 to 10 minutes later in its life cycle, the tower may not be suitable. The unsuitable tower may have brothers and sisters, however. A parent cloud that has produced one good tower will usually produce others. Do not give up too quickly, especially if a field of hard towers is growing below the aircraft.

When cloud penetration has been timed properly, the cloud will usually meet the qualification criteria (at least 1.0 gram per cubic meter and 1,000 feet per minute). The question then will be whether additional seeding opportunities are present within the prospective experimental unit. *If none are obvious, the request for a treatment decision should be delayed until additional seeding opportunities are present.*

Documentation of events during the flight is absolutely essential. The Flight Scientists should make notes (written and voice) throughout the flight. In addition, the Flight Scientists are reminded to make entries on the cloud pass form (fig. 8.2) after each cloud pass, and to fill out the evaluating weather conditions form (fig. 8.3) prior to selection of an experimental unit.

Once the Flight Scientist is satisfied that the cloud conditions within the prospective unit meet the above experimental unit criteria, he will radio the Operations Director at the Chiang Mai FOC and request a treatment decision. The Operations Director shall immediately open the next envelope in the appropriate set of cold cloud random decision instructions to ascertain the treatment decision; he shall then inform the Flight Scientist of the treatment decision. A separate set of randomization envelopes will be prepared for clouds whose base temperatures are warmer than 16 °C and those whose base temperatures are equal to or colder than 16 °C. The Flight Scientist will acknowledge receipt of the information by repeating it back to the Operations Director, and the Operations Director is to acknowledge whether the read back is correct.

8.6 Carrying Out the Treatment Decision

Once an experimental unit has been declared and the treatment decision ("seed" or "no seed") has been received from the Operations Director, experimentation can begin. Clouds whose tops have a hard cauliflower external appearance and adequate SLWC and updraft internally are to receive real (i.e., AgI flares) or simulated treatment. *The SLWC and updraft thresholds for pushing the seeding button are 1.0 gram per cubic meter and 1,000 feet per minute, respectively. The scientist/seeder aboard the aircraft may relax the updraft threshold as the need arises, but no seeding should be conducted if the measured SLWC and updraft go below 0.5 gram per cubic meter and/or 500 feet per minute.*

After the seeding or simulated seeding has begun, seeding 1,000 feet or less over the top of an especially vigorous hard tower is permitted. The basis for this allowance is the analysis of cloud data collected during the 1991 field season, which showed that a good estimate of cloud water content in small drop sizes can be made based on the visual appearance of the clouds alone.

Once the decision on a particular unit has been made, it is irrevocable, and cannot be changed, nor can the unit be eliminated from the sample. Only complete failure of the radar can result in elimination of a unit from the sample. Without the radar, no rainfall data will be available to evaluate the unit.

The seeding experimentation begins with the ejection of AgI flares into suitable cloud towers within the unit when the decision is to "seed," and the simulation of seeding when the decision is "no seed." During the simulated seedings, event switch No. 3, instead of the eject button on the flare control box, should be used to mark each simulated flare so that a record will appear on the flight data.

During the treatment operations, the Pilots and Flight Scientists are to *make certain that all seeding or simulated seeding passes take place within the confines of the experimental unit* (i.e., within 25 kilometers of the qualification point). The "cloud pointer" on the aircraft should have been used to mark the position of the qualification pass, and this pointer will be helpful initially in keeping the aircraft within the unit.

The Thai Air Force radar at Doi Ithanon will monitor the position of the aircraft to make sure that it always operates a safe distance from the Burmese border. Under no circumstances is the seeder aircraft to violate Burmese air space.

Regardless of the treatment decision, the flight patterns are the same. The object is to recognize what nature is trying to do with your particular cloud or cloud group, and then seed to enhance the natural tendencies. This process will usually require multiple passes through suitable young towers growing on the upshear flanks of the parent cloud, and the ejection of about one AgI flare per second while in suitable conditions.

Doing the seeding at the right time and place to be effective requires teamwork between the Flight Scientist and the Pilots. Care should be taken not to fly into mature large clouds that can beat up the aircraft and are not suitable for seeding in any case. This care generally means that young upshear towers should be worked at angles to the shear vector to avoid penetrating the large cloud, which is normally downshear. The echo cores can be located on the aircraft radar. Most cloud towers more than 5,000 feet above the aircraft will already have echo cores and be unsuitable. Flight patterns requiring a 90° left turn and then a 270° right turn (or vice versa) frequently are helpful, as are racetrack patterns that permit visual monitoring of the cloud on one of the legs of the racetrack and repenetration of suitable towers and seeding on the other. Sometimes, no set patterns are possible because of intervening cloud clutter, and the aircraft is flown in whatever way is necessary to get the job done.

The Flight Scientist should keep track of the clouds in the experimental unit to avoid disorientation and chaos. All missions should have two Flight scientists on board, one to direct the flight and pick the clouds and the other to record the flight data and do the real or simulated seeding. On the next flight, the Flight Scientists should switch positions to allow both to gain experience in all aspects of conducting the experiment.

A good unit is one that lasts a minimum of 1 hour following qualification and has 20 to 30 seeding passes which result in the ejection or simulated ejection of 100 or more AgI flares. These criteria cannot always be controlled, however, and one is left to make the best of a particular situation.

Seeding is to continue in the unit as long as suitable towers are present, regardless of the treatment decision. There will be no limit to the duration of seeding and to the amount of nucleant that is expended in each experimental unit. Seeding will continue as long as cloud conditions are suitable. Premature termination of "no seed" cases, because "we are not actually seeding" will bias the experiment. Nevertheless, methods of identifying and correcting for natural and human biases are being included in the analysis procedures.

The experimental unit is terminated if more than 1 hour has elapsed since the last seeding *and* if any echoes are no longer contained within its boundaries. The unit can also be terminated if it moves inside the 25-kilometer radar dead zone or if the center of the unit moves beyond 159 kilometers from the radar.

The experimental unit can also be terminated by failure of the seeder aircraft and/or the monitoring AARRP radar. These operational failures shall not, however, serve as the basis to discard the unit. A unit that has been qualified shall be evaluated for the duration of radar monitoring. To do otherwise would allow bias to enter into the evaluation.

8.7 Flare Seeding System Operation

Operating the seeding system is not difficult. To turn it on, push the fuse in to get power to the system. Pull the fuse out later to disarm the system. Before commencement of seeding, make certain that the "reset" toggle switch is activated several times until the audio signal is heard ("beep beep") and a red arm light is seen. The system is now set to the pole position. The first flare fired will come from position No. 1 on the downwind side of the rack.

The rotary switch must be turned to the next bank of 25 flares when the current basket of 25 has been emptied. The running count of flares on the video screen will tell you when this is about to happen. It inevitably happens during a cloud pass! In the event you lose track of the count, an audible beep sounds when it is time to rotate the switch. If you do not hear the beep and continue to fire flares from the same basket, *you will be "firing" from an empty rack*. This error has happened to individuals in other projects and is quite embarrassing.

Remember that an arm light must show before each flare is fired. If no light appears while firing within a particular basket of 25 flares, push the seed button until an arm light is obtained. If no arm light appears after several button pushes, the flare basket may be empty. Advance the rotary switch to the next basket to obtain an arm light. If one does still not appear, something may be wrong with the seeding system; help will be needed from technicians on the ground.

8.8 Return to the Chiang Mai Airport

The aircraft usually will return to the airport before dark. An alternate airport will be used in case of inclement weather. The Flight Scientists are reminded to turn off the hot-wire instrument and the two (deicing) heating switches as soon as a decision has been made to return to the airport. *LANDING AND STOPPING THE AIRCRAFT WITH THE HEATING SWITCHES STILL ON WILL DAMAGE THE INSTRUMENTATION!* It is also important to remember to turn off the seeding system by pulling out the fuse.

On the way back to the airport, one additional form should be completed, i.e., the experimental unit evaluation form (fig. 8.4). The two Flight Scientists should confer in completing this form and attempt to make an honest assessment of the quality of the experimental unit that they qualified.

Upon landing, all relevant information should be collected, including the flight video and floppy data disk. Mr. Anuchit will examine the seeding racks and flares for proper operation and record the results on the AARRP AgI flare expenditure form (fig. 8.5). Generation of the flight printout should begin immediately upon arrival in the Chiang Mai Airport aircraft operations center office. The cloud pass information must be extracted from the flight printout so that it will be available for the debriefing the next morning.

It is incredibly important that written documentation of each flight be prepared prior to the following morning debriefing, even if an experimental unit was not declared. These written summaries are essential for subsequent evaluations of the cold cloud experiment.

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AIRCRAFT CLOUD PHYSICS INSTRUMENTATION REPORT

Date: ________________ Aircraft ID: ____________________________

Pilot: ________________ Co-Pilot: ____________________________

Engine start time: ______ Engine stop time: ______________________

Total flight hours expended: __________

Time of Data system activation (LST): _________

Instrument Status

Instrument
Operational status

(put check mark on appropriate line)

	Fully	Partly	U/S	Comments
JW liquid water	_____	_____	_____	___________
Reverse flow temp.	_____	_____	_____	___________
Ball variometer	_____	_____	_____	___________
Dew point	_____	_____	_____	___________
Nose camera	_____	_____	_____	___________
Data recording system	_____	_____	_____	___________
Seeding system	_____	_____	_____	___________

Number of flare "button pushes" _____

Priority of Day for Analysis?

(mark your choice below)

High: _____ Medium: _____ Low: _____

Notes: A fully operational instrumentation system works properly the entire flight. A partly operational system functions intermittently or quits entirely at some time during the flight. When marking this option, please indicate when the system became inoperational during the flight in the comments section. A U/S (unusable) system does not function at all on a particular flight.

Figure 8.1.- Aircraft cloud physics instrumentation report form.

RECORD OF CLOUD PASSES

WEATHER TYPE

Date	Cld Base Height (m)	Cld Base Temp (°C)	Cloud ID	Time of Pass (s)	Position		Flight Alt. (mb)	Temp <Pass (°C)	Height C top >A/C (m)	Time in Cloud (s)	Mean TAS (m/s)	Cloud Radius (m)	Max Updraft (ft/min)	Max SLWC (ft/min)	Suit-ability (s)	Chemical Used	
					Lat.	Long.										Type	Amount (gm)

OBSERVER:

Figure 8.2.- Record of cloud passes form.

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EVALUATION OF WEATHER CONDITIONS PRIOR TO SELECTION OF AN EXPERIMENTAL UNIT

Date: ________________ Time: ________________ (LST)

Flight altitude (ft): ________________

Name of individual completing this form: ________________________________

Assessment of Individual Clouds (check appropriate response):

Most clouds up to this time have been hard (_____), average (_____), or soft (_____) in appearance, and most have had SLWC > 1 gm/m^3 (_____) or < 1 gm/m^3 (_____).

Cloud bases look hard and well defined (_____) or ragged and diffuse (_____).

Cloud towers near the seeding level are straight and erect (_____) or leaning and sheared (_____).

Assessment of Field of Clouds (check appropriate response):

Isolated (_____), scattered (_____), or numerous (_____) cloud towers are present at my flight altitude.

They are excellent (_____), average (_____), or poor (_____) in appearance.

Many Cbs (_____), a few Cbs (_____), or no Cbs (_____) are present within my view.

These Cbs are highly organized (_____), show some organization (_____), or have no organization (_____).

Upper cloud is present above my flight level (_____) or at my flight level (_____).

This upper cloud coverage is increasing (_____), staying the same (_____), or decreasing (_____) with time.

Overall Assessment:

In my assessment, the overall weather conditions for seeding are:

terrible (_____), poor (_____), fair (_____), good (_____), or great (_____).

Planned Course of Action:

My intentions are to cancel operations at this time (_____), to wait a while longer before I make my decision (_____), or to qualify a unit and begin experimentation (_____).

Figure 8.3.- Evaluation of weather conditions prior to experimental unit selection form.

COLD CLOUD EXPERIMENTAL UNIT EVALUATION

Date: ______________________________ Name: ____

Cloud base height: _______________ ft Cloud base temperature: ______________________ °C

Number of randomized experimental unit: ______________________________ (since program began)

Time of qualification pass: _____ LST

Position of qualification pass: _____° _____' _____" N; _____° _____' _____" E

Max SLWC for pass: _____ gm/m^3 Max UD for pass: _____ ft/min

Treatment Decision: _____ (seed) or _____ (no seed)

Number of cloud passes after qualification pass: _____

Number of cloud passes with real or simulated seeding: _____

Total number of button pushes: _____

Number of flares ejected: _____ (applies only to seed cases)

Time of last real or simulated treatment: _____ LST

Duration of treatment (time of last real or simulated seeding minus the time of the first real or simulated seeding): _____ h _____ min

I rate this experimental unit:

__________ Poor __________ Good

__________ Fair __________ Excellent

Comments:

____

____

____

____

____

____

____

Figure 8.4.- Cold cloud experimental unit evaluation form.

AARRP AGI FLARE EXPENDITURE REPORT

(Draw a line through expended flares; circle all flares still in the rack)

Date: ___________

196	197	198	199	200
191	192	193	194	195
186	187	188	189	190
181	182	183	184	185
176	177	178	179	180
171	172	173	174	175
166	167	168	169	170
161	162	163	164	165
156	157	158	159	160
151	152	153	154	155
146	147	148	149	150
141	142	143	144	145
136	137	138	139	140
131	132	133	134	135
126	127	128	129	130
121	122	123	124	125
116	117	118	119	120
111	112	113	114	115
106	107	108	109	110
101	102	103	104	105
096	097	098	099	100
091	092	093	094	095
086	087	088	089	090
081	082	083	084	085
076	077	078	079	080
071	072	073	074	075
066	067	068	069	070
061	062	063	064	065
056	057	058	059	060
051	052	053	054	055
046	047	048	049	050
041	042	043	044	045
036	037	038	039	040
031	032	033	034	035
026	027	028	029	030
021	022	023	024	025
016	017	018	019	020
011	012	013	014	015
006	007	008	009	010
001	002	003	004	005

Back of aircraft

Total flares fired: ____________________ Total misfires: ______________________________

Comments:

Figure 8.5.- AARRP AgI flare expenditure report form.

9. THE WARM CLOUD EXPERIMENT

9.1 Introduction

The purpose of the aircraft missions is to conduct warm cloud seeding operations on experimental unit convective cells and clouds contained within the randomized target area. Two pairs of target areas, a western and eastern pair of targets, have been selected for the Phase 2 warm cloud seeding demonstration project, based upon: (1) radar/rain gauge coverage, (2) similar topography, (3) mean 700-millibar wind direction, and (4) a rainfall correlation analysis (see fig. 9.1). These two pairs of target areas are located over the higher terrain, beyond the 12.5-kilometer radar dead zone established for the warm cloud experiment (see section 4—**Overview of the Design of the Demonstration Project**). Each target area measures about 30 kilometers long by 30 kilometers wide. At least a 20-kilometer buffer separates the two areas in each target area pair.

Approximate coordinates (rounded to the nearest minute of latitude or longitude) for the corners of the four target areas are listed in table 9.1 below.

Table 9.1. - Approximate coordinates for target area corners.

	TA-W1			TA-W2	
	Latitude	Longitude		Latitude	Longitude
NE	18° 10'N	98° 37'E	NE	17° 43'N	98° 43'E
SE	17° 53'N	98° 37'E	SE	17° 26'N	98° 43'E
SW	17° 53'N	98° 20'E	SW	17° 26'N	98° 26'E
NW	18° 10'N	98° 20'E	NW	17° 43'N	98° 26'E
	TA-E1			**TA-E2**	
	Latitude	Longitude		Latitude	Longitude
NE	18° 15'N	99° 00'E	NE	17° 43'N	99° 17'E
SE	17° 58'N	99° 00'E	SE	17° 26'N	99° 17'E
SW	17° 58'N	98° 43'E	SW	17° 26'N	99° 00'E
NW	18° 15'N	98° 43'E	NW	17° 43'N	99° 00'E

The western target area pair, TA-W1 and TA-W2, will be selected for demonstration project operations according to the randomized crossover design during the hours of 0900 to 1300 LST. During the hours of 1300 to 1800 LST, the eastern target pair, TA-E1 and TA-E2, will be selected for demonstration project operations. A separate set of randomization envelopes will be prepared for the western and eastern target area pairs.

The seeding of the clouds within the designated target area is done by introducing the $CaCl_2$ particles into the warm cloud treatment units. In the warm cloud seeding demonstration project, the AeroCommander high altitude aircraft is used for surveillance, experimental unit qualification, and cloud measurements. Two CASA aircraft are used to simultaneously seed the warm clouds in the randomly selected target area.

Ideally, the seeding should be done as low in the cloud as possible, consistent with safety and logistical considerations, but no higher than about 100 meters (300 feet) below cloud top. The two aircraft should be separated 1,000 feet vertically, and about five minutes in time.

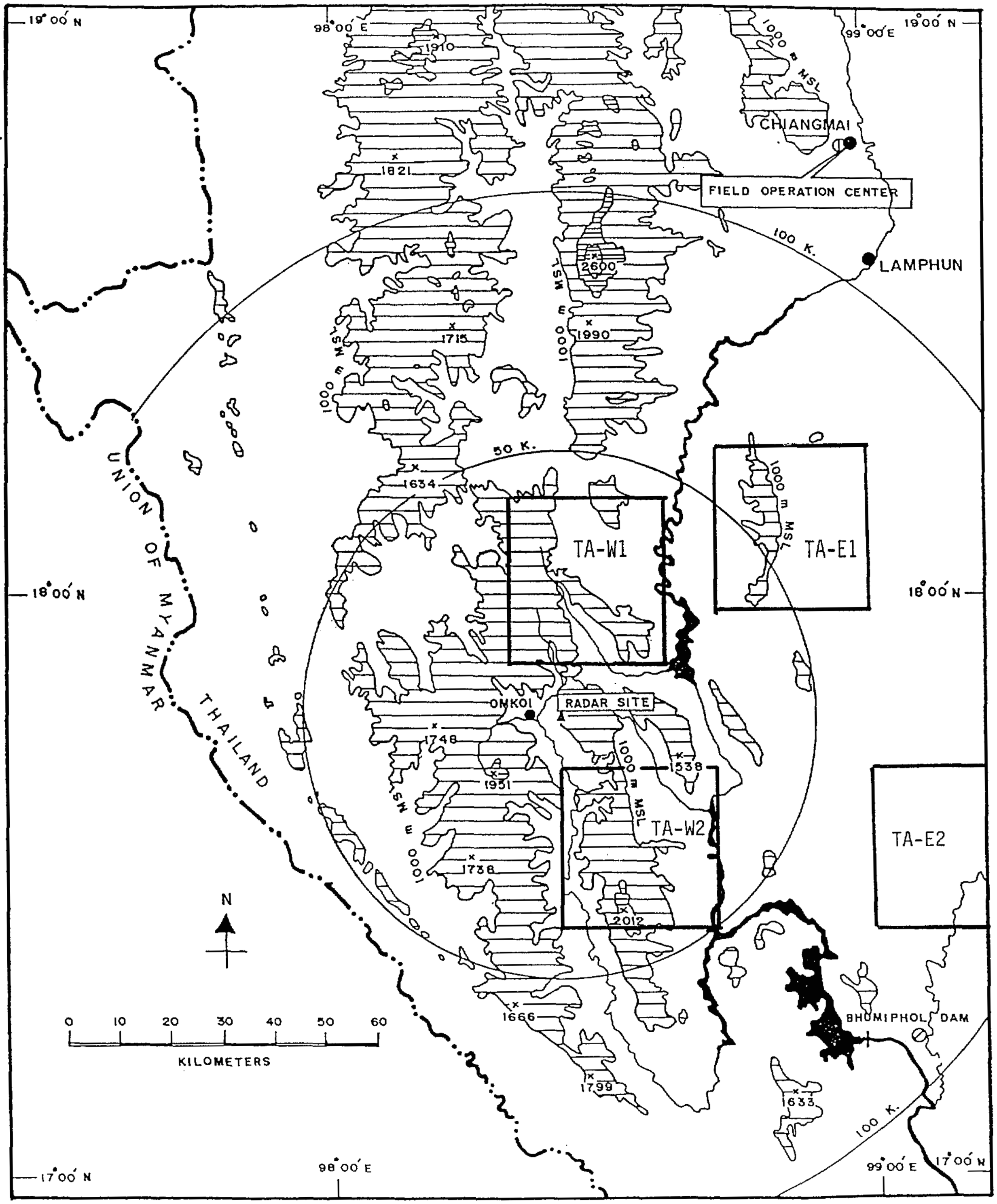

Figure 9.1. - AARRP Phase 2 project area showing warm cloud seeding target areas.

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The identification of suitable warm cloud conditions for seeding requires real time monitoring of cumulus clouds within the two target areas, including cloud top heights and cloud top temperatures. The AeroCommander 690B aircraft will be used for these purposes in the warm cloud seeding demonstration project.

On some occasions, no clouds suitable for warm cloud seeding will be qualified by the AeroCommander. The convective clouds could be too shallow, too widely scattered, suitable in only one target area, or some tops many be too cold. In such cases, the warm cloud seeding aircraft should return to Chiang Mai without expending seeding chemicals.

9.2 Decision to Launch the Aircraft

The first crucial decision point is the time to launch the AeroCommander aircraft. A normal fuel load will give about 4 hours aloft at about 15,000 feet. Another crucial point for the warm cloud seeding missions is the time to launch the warm cloud seeding aircraft. A normal fuel load will also give about 4 hours aloft at operational altitude (around 10,000 feet). Premature takeoff by either of these aircraft may mean that the fuel will run out before an experimental unit can be declared and treated. A late takeoff may result in some of the clouds growing too large to allow the qualification of an experimental unit.

Personnel at the AARRP radar site should monitor the presence and/or development of convective clouds over the target areas, beginning at 0800 LST (see section 10.4.2). As soon as convective clouds are observed in either target area, the observer at the radar site should immediately alert the Operations Director at the FOC. If the day has been declared a warm cloud experimental day at the Project Operations Briefing, and developing convective clouds have been observed in the target areas, the Operations Director should order the immediate takeoff of the AeroCommander and both CASA aircraft.

All things considered, it is best to launch the AeroCommander surveillance aircraft and the two CASA warm cloud seeding aircraft early, and use the AeroCommander observations to trigger the seeding operation as soon as possible after the warm cloud seeding qualification criteria are met.

9.3 Before Starting the Engines

AeroCommander Aircraft. — Several items must be addressed before the AeroCommander aircraft engines are started. First, the Flight Scientists should check the time with a reliable source. Second, although they are not essential to the warm cloud seeding experiment, the Flight Scientists should make certain that the hot-wire, liquid-water, sensing head is mounted on the aircraft. Third, the Flight Scientists should make certain that they have the following with them before entering the aircraft and closing the door: formatted floppy disks, video tape, relevant forms, notebook, pen, pencil, and clipboard.

Once on board the AeroCommander aircraft, complete the preflight checklist before power is applied to the DAS. Make certain that the DAS switches are set as shown in the checklist. The checklist in the plastic page-protectors in the flight notebook should always be used for this purpose.

CASA Aircraft. — Before starting the engines of the CASA warm cloud seeding aircraft, the Flight Technicians should check to make sure that each aircraft is carrying the appropriate amount of the $CaCl_2$ seeding chemical, and that they have the warm cloud experiment seeding report forms required to document the seeding mission. The CASA Pilots should make sure that the GPS unit on each of the two aircraft is working.

9.4 After Starting the Engines

AeroCommander Aircraft. — Once the preflight checklist for the AeroCommander has been completed and the engines are running, power to the DAS should be requested and the next portion of the checking procedure should begin. In activating the DAS, make certain to check the date and time against the standard. Enter corrected values at the keyboard if necessary. Make certain that the *lens cap has been removed* from the video camera. The video tape should be inserted into the recorder and taping (both voice and video) should begin. If the tape has been used to video tape more than one day, great care must be exercised to ensure that the current taping begins *at the end* of the taping for the previous day. Otherwise, valuable previous data will be lost (i.e., recorded over).

CASA Aircraft. — The Pilots need to coordinate with each other to ensure that the altimeters on the two aircraft *are set to the same altimeter setting*. The normal procedure should be to adjust the altimeters to the local Chiang Mai Airport altimeter setting just prior to takeoff. If this setting is not available, the instrument may be set properly by rotating the scale so that the indicated altitude is equal to the elevation of the airport. This procedure will enable the Pilots to maintain the 1000-foot vertical separation between the two aircraft during seeding operations.

9.5 Flying To and Around the Target Areas

All communications between the project aircraft and either the Operations Director at the Chiang Mai FOC or the Radar Operator at the AARRP radar site near Omkoi are to be made on FM frequency 155.825 megahertz. Because the two CASA aircraft will be flying in close proximity to each other, the Pilots should frequently inform each other of their aircraft's position to ensure safety and coordinate flight operations. Communications between the Pilots and the Thai air traffic control center and the Royal Thai Air Force Doi Ithanon radar are to be made on the assigned VHF frequencies.

AeroCommander Aircraft. — During the climb to en route flight altitude at the -5 °C level (around 19,500 feet), while the aircraft sounding is being made (by activating event toggle No. 1), the Flight Scientist directing the flight should watch the cloud development and form a mental picture of where the clouds are, their estimated depths and heights, how they are organized, and how rapidly they appear to be growing. The initial contacts with the Operations Director and the AARRP Radar Operator should be made at this time; the Radar Operator should brief the Flight Scientist on the distribution of evolving clouds as seen from the radar site. He may be in a better position to see the development of clouds, and this additional target information may prove to be quite helpful.

Once the AeroCommander arrives over the two target areas at surveillance altitude, the main task is to confirm whether clouds in the two target areas meet the warm cloud seeding qualification criteria. It is essential that the Flight Scientists are in constant communication with the Operations Director to obtain his guidance in arriving at final experimental decisions.

Arriving over the target areas at the -5 °C level will allow easy identification of convective clouds extending above -5 °C (based on Chiang Mai soundings, the mean height of this level is generally around 19,500 feet). The Flight Scientist should direct the AeroCommander over the two target areas at this altitude and visually survey the spatial distribution of the convective clouds within the target areas. If mid-level clouds are present, the aircraft may need to descend to a lower altitude where the spatial distribution of the clouds can be determined.

While surveying the clouds over the two target areas, the time should be used to complete the instrument status report form (fig. 8.1), and the assessment of the weather form (fig. 8.3) prior to requesting a randomized area decision. Copies should be carried on the aircraft at all times. A pencil should be used when filling out these forms so that any errors can be corrected. Although this task is always an annoyance to the Flight Scientist, the completed forms are valuable during the later analysis phase.

CASA Aircraft. — The two CASA aircraft will climb to altitudes of about 9,000 feet and 11,000 feet m.s.l. respectively, and fly to the predesignated rendezvous point between and just to the east of the target area pair selected for randomized seeding experimentation. The two aircraft should circle over this waypoint in the same direction, stay in radio communications with each other, and maintain relative position.

9.6 Qualification of an Experimental Unit

The warm cloud experimental unit shall have the following characteristics in qualifying clouds in the two target areas in accordance with the conceptual model:

> Multiple convective clouds at least 1 kilometer, but no more than 3 kilometers, in depth are present in *both* target areas. The presence of one or two isolated convective clouds at least 1 kilometer in depth in each area does not satisfy this criterion, but a line of clouds in each area with only a few towers 1 to 3 kilometers in depth does satisfy this criterion.

To confirm or better understand the conceptual model of warm cloud hygroscopic seeding, the data for each target area pair will be stratified as follows:

1. By cloud depth at the time of seeding (measured by AeroCommander).

2. By the presence or absence of radar echoes in either target of the target pair at the time of seeding (measured by radar).

3. By whether the eventual cloud top temperature is warmer or colder than -5 °C (measured by AeroCommander).

4. By the time elapsed after the experimental unit is qualified until the seeding operation is actually carried out.

The best results are expected for the stratification combination of moderately deep (about 2 kilometers) clouds with no radar echo at the time of seeding. In view of the results of the numerical modeling experiments given in appendix D of "Volume 2—Demonstration Project Design," it remains to be seen whether seeding will have a greater effect on the cold clouds or warm clouds. This question is, perhaps, the most interesting aspect of the warm cloud seeding demonstration project from both the scientific and user viewpoints.

9.7 Carrying Out the Treatment Decision

9.7.1 Preseeding passes by the AeroCommander

If the Flight Scientist has confirmed that numerous convective clouds are present over each area, the AeroCommander should *descend to the altitude of cloud top height and fly a quasi-straight line lengthwise over both target areas.* This flight path will enable the Flight Scientist to confirm that the criterion for qualifying an experimental unit has been met (see section 9.5). These passes should take place near the upwind side of the target areas. During these passes, the Flight Scientist should *identify the preentered waypoints that best fit the tracks of the AeroCommander over both target areas.*

If the convective clouds do not qualify for an experimental unit, the Flight Scientist should then repeat the passes over the target areas until either 1) the clouds develop and meet the qualification criterion, or 2) the mission is terminated and all aircraft return to Chiang Mai. During these passes, the Flight Scientist should keep the Operations Director informed of the cloud top heights and winds observed at 10,000 feet.

9.7.2 GPS preentered waypoints for seeding tracks

The GPS aircraft navigation units installed in the aircraft are required for conducting warm cloud seeding operations. User preentered "waypoints" will be used to identify the beginning and ending points for each seeding track. Six (6) north-south seeding tracks for each target area should be established. The first seeding track should be located on the western edge of each target area; the other five (5) should be located parallel to and east of the first seeding track with a spacing of 2 minutes of longitude. "Waypoints" corresponding to the beginning and ending points of these seeding tracks should be preentered in the CASA and AeroCommander GPS units to facilitate the seeding operation. Each user preentered waypoint will be identified by three alphanumeric characters; either the letter "N" for north or "S" for south, followed by a two-digit number.

9.7.3 Declaring an experimental unit

Timing is everything in conducting airborne seeding operations. Environmental and cloud conditions change constantly. As little as 5 to 10 minutes after it is decided that conditions are suitable for seeding, the situation may change. Thus, the time evolution factor must be considered in qualifying a seeding case and experimental area. This consideration should not present a problem because the seeding aircraft will already be on-station when the decision to seed is made. Nevertheless, the time elapsed after initial qualification that seeding is actually carried out should be recorded and used to stratify the data during the analysis of results.

When the Flight Scientist on the AeroCommander determines that the convective clouds within *both* target areas meet the qualification criteria for experimental units, he will radio the Operations Director at the Chiang Mai FOC and request a treatment decision. The Operations Director shall immediately open the next envelope in the appropriate set of warm cloud random decision instructions to ascertain the randomized target area decision; he shall then inform the Flight Scientist of the target area decision. The Flight Scientist will acknowledge receipt of the information by repeating it back to the Operations Director, and the Operations Director is to acknowledge whether the read back is correct.

The Flight Scientist will then inform the Operations Director of the preentered waypoints he identified for the randomly selected target area that best fit the last pass made by the AeroCommander. The Operations Director should repeat back the waypoints and give his concurrence for the seeding track. *The specified seeding track should always start at the end of the target area that borders the buffer area.*

Immediately after receiving the randomized decision and seeding track confirmation, the AeroCommander Flight Scientist will contact the Pilots of the CASA warm cloud seeding aircraft and notify them of which target area to seed, and the beginning and ending waypoints for the seeding track. During this time, the Pilot of the AeroCommander should ascend and take a position well above the target areas, where the seeding operations and the development and movement of both seeded and unseeded clouds will be monitored. It will be necessary to ascend as high as the -5 °C level to document whether convective tops grow above this level during and after the seeding operations.

More than one warm cloud experiment may be conducted on a given day, provided that the seeding criteria are met and a suitable time buffer (minimum of 60 minutes) is maintained between the two experiments. The time required for the warm cloud aircraft to return to Chiang Mai, refuel and reload seeding chemicals, and return to the target areas should allow an adequate time buffer.

9.7.4 Executing warm cloud seeding operations

Once the CASA aircraft are instructed to start the seeding operation, every attempt must be made to carry it out. The seeding experimentation begins with the ejection of $CaCl_2$ in the clouds in the experimental area that has randomly been selected for seeding. During the seeding operations, the Pilots and Flight Technician on the seeding aircraft are to make certain that all seeding passes take place along the prescribed seeding track and within the confines of the experimental unit, i.e., the randomly selected target area.

Seeding is carried out by two CASA aircraft flying together, as indicated in table 9.2, where CASA No. 1 is at the highest altitude and CASA No. 2 is at the lower altitude. The desired altitudes and pattern of each seeding track and the amount of the $CaCl_2$ seeding chemical dispensed are summarized in table 9.2.

The first seeding pass should be made along the track defined by the two waypoints provided, beginning at the buffer end of the target area. The CASA Pilots will fly to the first waypoint, approaching from the unseeded target area. They will use the GPS to line up vertically over the beginning waypoint and then to fly to the ending waypoint. The Pilot of the lower CASA will lag 5 minutes behind the higher CASA so that he might see the other CASA during periods when they are both out of the convective clouds.

After the two CASA aircraft reach the ending waypoint, they should make a standard 90° turn together (it is recommended that they always turn in the direction away from Burma). After they have completed the 90° turn, they should make a standard 270° turn together in the opposite direction. This sequence will bring the aircraft back to the seeding track heading in the opposite direction. As they complete this turn, they should line up on the ending waypoint for the first seeding pass, which will serve as the beginning waypoint for the second seeding pass.

Table 9.2. - Warm cloud seeding operations.

Aircraft	Seeding Track	Seeding Altitude	$CaCl_2$
Pass No. 1			
CASA No. 1	Straight line (dropping $CaCl_2$ continuously in or over cloud	As low in cloud as possible, but no higher than ±300 ft below cloud top	600 kg
CASA No. 2	Straight line (dropping $CaCl_2$ continuously in cloud	1000 ft below and 5 min behind CASA No. 1	600 kg
Pass No. 2			
CASA No. 1	Straight line (dropping $CaCl_2$ continuously in or over cloud	As low in cloud as possible, but no higher than ±300 ft below cloud top	600 kg
CASA No. 2	Straight line (dropping $CaCl_2$ continuously in cloud	1000 ft below and 5 min behind CASA No. 1	600 kg

The CASA seeding track should be a straight line near the upwind side of the target area, or along a line of convective clouds. While on a seeding pass, the seeding aircraft should fly at a constant speed of about 110 knots IAS (indicated airspeed) (1 knot = 0.5144 meters per second), or slower if possible, and the $CaCl_2$ seeding chemical should be dispensed continuously (whether clouds are present or not) at a constant rate of about 80 kilograms per minute or faster. (At about 10,000 feet, with a temperature of 12 °C, an IAS of 110 knots converts to a TAS (true airspeed) of about 130 knots. At this aircraft speed and seeding rate, the CASA would seed for 15 minutes along a single track about 51 kilometers long.) Because the length of the two warm cloud experimental target areas has been set at 30 kilometers, the CASA seeding aircraft should dispense the 1200-kilogram $CaCl_2$ payload during two 7.5-minute seeding tracks of about 25 kilometers each.

From the time the CASA aircraft start their initial seeding pass until they complete their second seeding pass, the Flight Technician should record, on a minute-by-minute basis, the altitude and GPS position of the seeding aircraft. They should also record how many bags of seeding material were released on each seeding pass and how many bags, if any, were left over after the mission.

9.7.5 Postseeding passes by the AeroCommander

The Flight Scientist on the AeroCommander should keep track of the clouds in the target area for the experimental unit. The "cloud pointer" on the AeroCommander aircraft should have been used to mark the position of the target area upon qualification, which will help the Flight Scientist keep track of the clouds being seeded. However, the AeroCommander should alternately fly over both of the two target areas during seeding to collect data from both seeded and unseeded convective clouds.

As soon as the CASA aircraft have completed their two seeding passes, they will head back to Chiang Mai and the Pilots will notify the AeroCommander Pilot that the target areas are clear. The AeroCommander will then proceed to make its postseeding measurement passes over the two target areas. These passes should be made at 10,000 feet, starting with the seeded target area, and entering the area at the far end from the buffer area.

The four waypoints identified during the last "preseeding" passes over the two target areas should be adjusted by the Flight Scientist, based upon the observed 10,000-foot wind speed and direction, to account for the potential "drift" of the convective clouds during the CASA seeding operations. However, a line of convective clouds could develop over the higher terrain and remain nearly stationary for some time.

Before the AeroCommander descends to 10,000 feet, the four "drifted" waypoints for the postseeding passes should be entered in the Pilot's GPS. The Pilot of the AeroCommander will descend to 10,000 feet and fly the specified tracks. During the postseeding passes over both target areas, the Pilot should attempt to fly through as many convective clouds as possible along a quasi-straight line.

9.7.6 Termination of the experimental unit

The AeroCommander's Flight Scientist will determine when the first experimental unit has ended. This will normally be 1 hour after the end of CASA seeding operations, during which time the AeroCommander will make the postseeding passes over both target areas at 10,000 feet. The AeroCommander will return to Chiang Mai after the experimental unit has been terminated.

The experimental unit can also be terminated because of mechanical problems with the CASA seeding aircraft, problems with one of the GPS units on the aircraft, or complete failure of the monitoring AARRP radar system. Without the radar, little rainfall data will be available to evaluate the experimental unit. These operational failures shall serve as the basis to discard the unit.

9.8 Hygroscopic Seeding System Operation

Operating the seeding system is quite easy. The dispensing units are hoppers that exhaust under the fuselage of the CASA aircraft. Just prior to dispensing, the $CaCl_2$ seeding chemical bags are opened, and their contents are poured into the dispensing hopper. Care must be exercised in dispensing the chemicals at the required seeding rates; otherwise, considerable variability can be introduced at this stage of the experimental procedure.

9.9 Return to Chiang Mai Airport

The aircraft usually will return to the airport before dark. An alternate airport will be used in case of inclement weather. The Flight Scientists on the AeroCommander are reminded to turn off the hot-wire instrument and the two (deicing) heating switches as soon as a decision has been made to return to the airport. *LANDING AND STOPPING THE AIRCRAFT WITH THE HEATING SWITCHES STILL ON WILL DAMAGE THE INSTRUMENTATION!*

On the way back, one additional form should be completed, i.e., the warm cloud observation report (fig. 9.2). The Flight Scientist on board the AeroCommander aircraft should complete this form. He should also attempt to make an honest assessment of the quality of the warm cloud experimental unit that was qualified; this assessment should be entered on the cloud observation report.

Upon landing, all relevant information should be collected, including the flight video and floppy data disk from the AeroCommander aircraft. The seeding hoppers on the CASA aircraft will be examined and cleaned to ensure proper operation; the results of this examination and the amount of $CaCl_2$ seeding chemical dispensed should be recorded on the warm cloud seeding report (fig. 9.3). Upon arrival in the Chiang Mai Airport aircraft operations center office, generation of the flight printout from the DAS on the AeroCommander can begin, so that it will be available for the debriefing the next morning.

It is incredibly important that written documentation of each flight be prepared prior to the following morning debriefing, even if an experimental unit was not declared. The Flight Scientist on the AeroCommander aircraft should write up the summary for the mission; however, the Flight Technicians on the CASA aircraft should provide information on the seeding operations. These written summaries are essential for subsequent evaluations of the warm cloud experiment.

CLOUD OBSERVATION REPORT

AeroCommander HS-TFG　　　　T/O time: _____ L/D time: _____

Date: ________　　　　CREWS: ________________

____

Time (hh:mm)	Latitude	Longitude	Heading (° Az.)	Altitude (ft)	Area No.	Mean Cld Base (ft)	Max Cld Top (ft)	Cloud ID

OBSERVER: ________________

Figure 9.2. - Warm cloud observation report.

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WARM CLOUD SEEDING REPORT

Aircraft: ________ T/O Time: ________ Crews: ________

Date: ________ L/D Time: ________ ________

Seeding No.	Flight Time		Seeding Material		Start			Stop			Heading	Altitude (ft)
	T/O	L/D	Type	Amount	Time	Lat.	Long.	Time	Lat.	Long.		

OBSERVER: ________________

Figure 9.3.- Warm cloud experiment seeding report.

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10. THE RADAR SITE PROGRAM

10.1 Introduction

The AARRP radar is *absolutely essential* to the randomized cold cloud and warm cloud seeding experiments because of its use in performing the following functions:

1. Observing the evolution of the rain cells in real time and providing the information on the locations of intense radar echoes (large Cbs) that could affect the experimental units and aircraft/air crew safety.

2. Deriving the vertical profile of the winds, which will be used to obtain the translation vector of the cold cloud experimental units.

3. Evaluating the three-dimensional structure and evolution of the precipitation in all clouds within 165 kilometers of the radar and evaluating the effect of seeding by comparing the properties of the seeded cells to those of the unseeded cells.

4. Obtaining areal rainfall measurements after combination with the "calibration" readings of AARRP rain gauges for use in the seeding experiments, and also for use in NASA's cooperative TRMM (Tropical Rainfall Measuring Mission).

The main operational and research radar for the AARRP is an EEC (Enterprise Electronics Corporation) Model DWSR-88S, S-band (10-centimeter) Doppler Weather Surveillance Radar with a 1.2° conical beam. The AARRP radar is situated on a hill about 9 kilometers east of Omkoi (17° 47'54" N; 98° 25' 57" E) at an elevation of 1,160 meters (3,805 feet). The surrounding terrain is below 1° elevation, except between 225° and 275° azimuth, where one hill-top extends up to 2.1° elevation. During the field operational period, the radar will be operated 24 hours per day. All reflectivity and Doppler velocity data will be recorded on TK70 and/or 8-millimeter tape cartridges.

The evaluation of the cold cloud experiment's seeding effect on the individual cells will be based primarily on the evolution of the precipitation radar echoes in space and time. For the warm cloud experiment, the evaluation will be based on the statistical comparison of radar estimated rainfall over the two fixed target areas and a comparison of the radar echo histories in seeded and unseeded clouds. If the radar does not function, or if the data did not go on tape properly, the day and its random unit(s) have been lost.

10.2 Radar Calibrations and Maintenance

Radar calibrations and maintenance are crucial to the success of the radar program. Therefore, radar personnel are urged to follow calibration and maintenance procedures provided by EEC and NASA in training courses and manuals on these subjects.

10.3 Radar Operations

The radar will be operative during ALL of the AARRP field season, except for down time for maintenance and calibration. During non-operational periods, the radar will be operated in the SURVEILLANCE mode. The purpose of the SURVEILLANCE mode is to obtain areal rainfall measurements over the study area (out to 165 kilometers), and to monitor the evolution of rain cloud systems. The SURVEILLANCE mode is composed of base scans (antenna tilt angle of 0.6°) every 5 minutes, and a complete volume scan replacing the base scans every 30 minutes.

During operational days, the radar will be operated in OPERATIONAL mode whenever precipitation echoes exist within 140 kilometers of the radar, or whenever project aircraft have been launched for surveillance and/or experimental missions. The OPERATIONAL mode is programmed as the default option of the radar.

In the OPERATIONAL mode, the radar will be operated in a hybrid volume scan, using lower PRF (pulse repetition frequency) and larger sample size at the lower tilt angles in order to reject ground clutter and avoid second-trip echoes. At the higher tilt angles, the radar will use higher PRF and smaller sample size to save scan time, such that *scanning of the whole volume of the troposphere at the radial distances of 25 to 165 kilometers from the radar will be completed every 5 minutes.* The tilt angles are selected to provide a vertical resolution of 1.5 kilometers at the range of 100 kilometers, or at an altitude of 12 kilometers. To optimize the scan time, the vertical resolution degrades gradually at higher altitudes. This resolution is obtained by the following set of 18 tilt angles: 0.6, 1.0, 1.8, 2.6, 3.4, 4.2, 5.0, 5.8, 6.7, 7.9, 9.3, 10.9, 12.8, 15.1, 17.6, 20.3, 23.5, and 27.1°.

The volume scan is a hybrid radar task, which consists of the following three sub-tasks:

1. *Low-level base scan for long-range measurements of Z (reflectivity) in unblocked sectors.* The base scan is set at a tilt angle of 0.6°, which is half of the radar beam width. This width will provide the best possible measurements of reflectivity at long ranges in the unblocked sectors. The PRF is 650 pulses per second, so that the unambiguous range is at 268 kilometers. These data will be used only beyond the range of most ground clutter. To increase the sensitivity and not reject valid data while saving scan time, the sample size is to be set to 32 and the clutter filters are to be set so that in the case of ambiguity between meteorological targets and ground clutter, the data point in question will be recorded.

2. *The low part of the operational volume scan for clutter rejection.* The second part of the hybrid scan is made up of tilts at 1.0° and 1.8° that top all of the mountains in the vicinity, except to the southwest where a mountain-top blockage reaches a peak value of 2.1° above the horizon. The emphasis here is on best clutter rejection, together with close and medium range Z measurements. This measurement is to be achieved with a PRF of 560 and a sample size of 64 pulses per bin and sensitive clutter filters.

3. *Medium and high parts of the volume scan.* The third part of the hybrid scan is made of 15 tilt angles that provide the three-dimensional structure of the precipitation echoes above the elevations at which ground clutter may contaminate the data. The 15-tilt sequence is 2.6, 3.4, 4.2, 5.0, 5.8, 6.7, 7.9, 9.3, 10.9, 12.8, 15.1, 17.6, 20.3, 23.5, and 27.1°. The emphasis is on covering the volume with the best spatial resolution. This procedure requires maximizing the number of tilts and minimizing the scan time per tilt. The limiting factor here is the maximum rate of rotation of the antenna, which is 5 revolutions per minute. To maximize the quality of the data, we transmit the largest possible number of pulses per bin that can fit in a 12-second antenna sweep. Therefore, the PRF is to be set to 934, which gives a sample size of 30 pulses per bin and an unambiguous range of 160 kilometers.

Before any aircraft are launched, the radar should be scanning in the OPERATIONAL volume-scan mode, stepping the antenna upward to a maximum of 27.1°, and then returning to the 0.6° base scan. The Operations Director will monitor the remote radar display at the Chiang Mai FOC, and will be responsible for communicating to the Flight Scientists radar information guidance useful in carrying out the treatment. However, the Radar Operator should also monitor his radar display and should be prepared to assume this role should the remote radar display at the FOC be inoperative, or if he is so directed by the Operations Director.

In executing the cold and warm cloud treatment operations, the Flight Scientist may require radar support in making certain that all seeding or simulated seeding (cold cloud experiment only) passes take place within the confines of the experimental unit. Therefore, the Radar Operator as well as the Operations Director should continuously track the cold cloud experimental unit by moving it along with the motion evident in the radar echoes nearby. During warm cloud experiments, they should track the motion evident in the radar echoes over the two target areas.

Monitoring of the experimental unit(s) is to continue until they disappear from the radar scope. This monitoring may require radar operation for the randomized effort well into the evening hours. At the conclusion of OPERATIONAL mode data collection, a portion of each tape should be played back to verify that data actually went on tape. Each TK70 and/or 8-millimeter tape cartridge is to be labeled with a start and end date/time.

This process can then begin anew the next day. After four or five days in a row of this regimen, everyone will become exhausted. Special care is needed at this time to ensure a continued safe operation, and to ensure that no serious mistakes are being made in data collection and the archival process.

10.4 Other AARRP Tasks at Radar Site

10.4.1 Upper air soundings

Unless the day has been declared "stand down" by the Operations Director the previous afternoon, project technicians will use the RD-65A rawinsonde system to make a 0700 LST (0000 GMT) upper air sounding at the radar site. This sounding can provide valuable information on the potential for the development of convective clouds in the vicinity of the radar site, especially over the two target areas selected for the warm cloud experiments. On each operational day, a second upper air sounding will normally be made at 1300 LST (0600 GMT); however, the Operations Director can request a sounding from Chiang Mai instead. The primary purpose for the afternoon sounding is to provide upper air data for the evaluation of the randomized experimental units.

Each project sonde released should be tracked at least to the 400-millibar level. If the sonde is lost before it reaches the 400-millibar level, a second sonde should be prepared, released, and tracked. The data recorded from the sonde will be coded into the format required by SONDE program module PJRAOB. The coded data will be entered into a data file on a PC at the radar site. This data file will be sent via radio data link to the FOC in Chiang Mai for SONDE program processing. Each morning, a second data file consisting of hourly temperatures recorded at the radar site the previous day must also be sent to the FOC. The hourly temperature data are needed for SONDE program module ANALYZR.

10.4.2 Meteorological surveillance

The Radar Operators (or other designated technician) on duty between the hours of 0800 and 1800 LST also will provide a "metwatch" for the project. This procedure requires the responsible individual to go outside and make frequent (e.g., every 30 minutes) visual observations of the clouds within sight. Of particular interest is the development of convective clouds; however, information on the amount and movement of middle and high clouds is also useful. Hourly reports should be made by radio or phone to the Operations Director or the Satellite Data Analyst at the Chiang Mai FOC. All visual observations made from the radar site should be recorded on a daily "metwatch" visual observations log.

10.4.3 VHS movie camera operation

In addition to the visual "metwatch," a VHS movie camera will be used to obtain video documentation of convective cloud development that can be used in the subsequent evaluations of warm cloud experimental units. *It will be especially important to document the onset of convective cloud development over the two target areas for the warm cloud experiment caused by solar heating of the terrain.* The subsequent evolution of the convective clouds over the target areas during the day also must be evaluated. Consequently, interval recorded (time lapse) video pictures are needed each day, between about 0800 and 1800 LST. However, whenever a cold cloud experimental unit is within visual range of the radar site, the camcorder will be moved temporarily to document the cloud's visual development.

In the interval recording mode of operation, the VHS movie camera automatically makes recordings of about 1 second in duration at 50-second intervals. However, the initial recording will last for about 5 seconds. The interval recording will continue for a maximum of 10 hours, after which the VHS movie camera will turn itself off.

If the VHS movie camera is ONLY used in the interval recording mode for 10 hours each day, a T120 VHS tape should record video pictures for about 10 days. Care must be taken when the interval recording is started at 0800 LST each morning to ensure that the current video recording begins at the end of the video recording for the previous day. Also, be sure that the correct time and date are displayed in the EVF (Eyepiece Viewfinder). When the camera is properly set to the interval recording mode, "INT" will appear in the EVF.

The VHS movie camera will probably be pointed toward 020° and/or 140°, that is, toward target area TA-W1 and/or target area TA-W2, respectively. *The VHS movie camera must not be exposed to direct sunlight through the window. Excessive heat will deform the camera's body or cause other damage to the unit. The camera should also not be operated outdoors when blowing dust or rain could get in the camera.* (Read the **Cautions** section, pages 53-54, in the operating instructions manual.)

10.4.4 Data shipments

The radar data tapes, video tapes, the radar log forms, the original rawinsonde data records, and the visual cloud observation forms should be stored in a secure and environmentally safe protective cabinet at the radar site. About every two weeks, the radar tapes, video tapes, and forms containing daily data should be transported to the AARRP FOC in Chiang Mai; an inventory list should accompany each shipment to ensure that no data are lost. The radar tapes should be subsequently shipped to RRRDI in Bangkok (recommend monthly). At RRRDI, the radar data tapes should be copied onto 8-millimeter tapes and the tape copies mailed to NASA for the NASA TRMM program.

11. THE AARRP RAIN GAUGE PROGRAM

11.1 Resources

A total of 45 to 48 recording rain gauge sites have been installed in the AARRP study area in the arrays shown on figure 11.1. The gauges are Weather Measure Model P501-1 tipping bucket gauges with an orifice diameter of 20.0 centimeters (7.874 inches). Each gauge uses a Qualimetrics Model No. 61126 solid state event recorder and a Model No. 65351 Data Cartridge. After removal of the data cartridges from the gauges, the data are downloaded onto PC (3.5-inch double-sided, double density) diskettes with a Qualimetrics Model No. 65353 Data Translator. The data cartridges are then reinitialized for later reuse.

All project recording rain gauges have been installed in clearings that are large enough to accommodate the landing of a helicopter. The gauges are surrounded by a wire-mesh fence, and the gauge openings are slightly above the top of the fence.

Mr. Noppadol Anukul is in charge of the rain gauge program. He will be based at the AARRP Field Operations Center at Chiang Mai Airport. He should service all of the recording rain gauge sites by helicopter, or, where possible, by 4-wheel drive vehicle on a monthly basis. Tasks to be accomplished at each site and also after returning to his home base are listed in the following section.

11.2 Procedures

During the regularly scheduled trip to each gauge location, Mr. Noppadol will do the following:

11.2.1 At the field rain gauge site

1. Remove the rain gauge cover and manually tip the rain gauge bucket 10 times; tip at the rate of about once each second. The red light on the data cartridge should blink 10 times.

2. Momentarily press the white button on the data logger (recorder); the light on the data cartridge should blink once.

3. Carefully remove the combination of the data logger and data cartridge. Remove the data cartridge from the logger. Be careful not to touch the white button again on the data logger.

4. Enter the site name and number, the data logger number, the removed data cartridge number, the date and time, the number of manual bucket tips, and any comment on the data onto the servicing log sheet.

5. Check the rain gauge and its calibration, clean and recalibrate as necessary, and record an entry into the maintenance record.

6. Insert a previously initialized data cartridge into the data logger, being careful not to press the white button on the data logger. Enter the new data cartridge number onto the servicing log sheet.

7. Insert the data logger with the installed data cartridge into the banana jacks on the base of the rain gauge. Press the white button on the data logger and observe that the light blinks once.

8. Manually, slowly tip the bucket on the rain gauge 10 tips; observe that the red light blinks 10 times. Enter the start date and time on the servicing log sheet.

9. Replace the cover on the rain gauge and secure the cover bolts. Cut down any significant growth of vegetation inside the fence enclosure.

11.2.2 At the AARRP Field Operations Center

1. The rainfall data are to be downloaded onto a 3.5-inch diskette which contains a copy of the GEMS software. (Note: complete instructions are listed in *The Recording Rain Gauge System Simplified Set-Up Procedures* manual). The completed log sheet for the data downloading is to be kept with the appropriate diskette.

2. The data cartridge for each gauge is to be reinitialized after the data have been downloaded to diskette; however, before reinitializing the cartridge, check the diskette to make sure that the data have been downloaded successfully.

3. Make two copies of each data diskette and log sheet.

4. Store the original data diskettes and log sheets and the two copies at the Field Operations Center in a secure and environmentally safe protective cabinet. One of the copies is to be used in the data quality control process and is to be retained for backup data records; the second set is for NASA.

11.3 AARRP Rain Gauge Network Changes

The design of the AARRP Phase 2 requires some changes in the AARRP's rain gauge network. In particular, gauges are needed within and downwind from the two new eastern target areas for the warm cloud seeding experiments. Figure 11.1 shows most of the 1993 rain gauge network; however, downwind stations on north-northeast, east-northeast, and south-southeast radials from the radar are not shown. The complete AARRP rain gauge site list is given in table 11.1. This table gives the locations, elevations, and data record starting times for all past and present sites. The table also gives the ending dates for gauges that were removed and relocated to other sites.

11.3.1 Rain gauge data objectives

The redesign of the rain gauge network for Phase 2 was done with the following objectives in mind:

1. Keep all rain gauge sites presently located within the four target areas for the warm cloud seeding experiment.

2. All of the target areas must have at least a few rain gauges.

3. Rain gauges need to be located downwind from the two eastern target areas.

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4. Rain gauges are needed along different radials from the radar site, extending out to 150 kilometers if possible.

5. Clusters of rain gauges are needed to sample both convective rainfall and rainfall from stratocumulus clouds over the higher upwind terrain during the southwest monsoon season.

11.3.2 Selection of rain gauge sites to drop from network

The redesign of the network required that some of the existing rain gauges be moved to new locations. The rain gauge sites to be dropped were selected on the following bases:

1. *Poor data records* - Table 11.2 lists the data records for all of the AARRP rain gauges. After excluding sites that could not be moved based on the criteria listed above, the sites selected to be removed were 061, 072, 091, and 094.

2. *Valley sites providing redundant data* - Two sites were located in the valley to the south of TA-W2 that were selected on this basis, viz., sites 083 and 095.

3. *Downwind sites having low priority* - With the selection of the four new target areas, it was determined that the three downwind gauges located to the south-southeast of the radar, viz., 322, 324, and 331, would better serve the data needs of the project if they were relocated to within and downwind from TA-E2.

11.3.3 New rain gauge locations

Figure 11.1 shows the locations for rain gauge clusters and the radials along which the downwind sites are or will be located. Specific guidelines are as follows:

1. *Rain gauge radials* - Gauges are already installed at sites along the 025°, 070°, and 190° radials from the radar; gauges are required along the 105° radial. Four gauges are presently available for installation along this radial; two should be installed within TA-E2, and two should be installed downwind from TA-E2 out to 150 kilometers. The following gauges are already installed along the radials listed:

   025° radial: 013, 334, 325, 335, 321, and 344

   070° radial: 002, 323, 333, 332, 343, and 311

   190° radial: 054, 063, 073, 082, 092, and 093

2. *Rain gauge clusters* - A cluster of five rain gauges should be installed within TA-E1. Clusters of five rain gauges having good data records already exist to the west and south-southwest of the radar as follows:

   West cluster: 042, 051, 052, 053, and 345

   South-southwest cluster: 073, 081, 082, 092, and 093

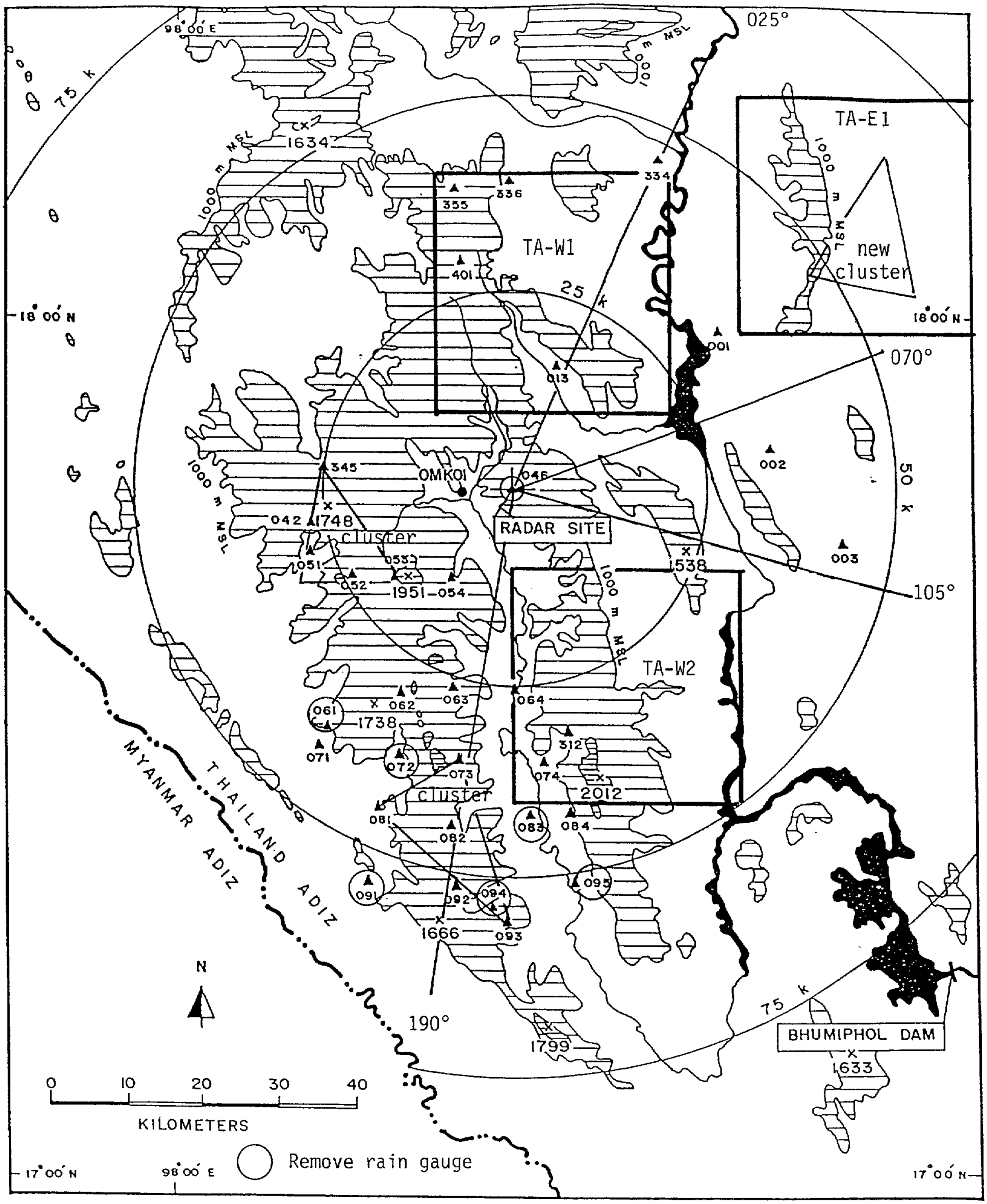

Figure 11.1. - AARRP rain gauge locations and changes for AARRP Phase 2.

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Table 11.1. - AARRP rain gauge site list (lat. and long. given in degrees and hundredths of minutes).

Station No.	Name	Location Lat. N	Long.E	El. (ft)	Start mm/dd/yy	End mm/dd/yy
001	Wang Lung	175903	984138	1100	06/24/91	
002	Pong Thung	175127	984524	1150	06/24/91	
003	Ban Mai	174424	985027	1650	06/24/91	
011	Hang Luang	175941	981721		07/08/91	04/05/92
012	Mae Tom	175970	982088		06/07/91	04/04/92
013	Duang Chan	175632	982889	2950	06/08/91	
021	Phi Pan	175497	980774		07/08/91	04/05/92
022	Sa Ngin	175331	981414		07/07/91	04/05/92
023	Huay Bong 1	175445	981608		04/29/91	04/05/92
024	Yong Ku	175622	982047		01/10/92	04/06/92
025	Pang Mong	175475	982527		06/07/91	04/04/92
031	Mae Pa	no data for this site			10/09/91	04/05/92
032	Bai Na	175156	980837		04/29/91	04/05/92
033	U Tum	175168	981262		07/07/91	04/05/92
034	Pa Pun	175141	981718		07/07/91	04/04/92
035	Huay Bon	175104	982990		06/07/91	04/05/92
036	Yang Kaeo	175068	982699	3550	06/08/91	04/13/93
041	Kui Luang	174684	980686	4400	04/29/91	09/19/92
042	Mae Khong	174559	981084	2900	04/29/91	
043	Mae Lop	missing	missing		09/13/91	04/05/92
044	Tong Sard	missing	missing		07/07/91	04/06/92
045	Ban Luang	174699	982204	2600	06/21/91	04/02/93
046	Radar Site	174790	982590	4690	03/15/91	
051	Sa Tae	174364	981055	2150	04/29/91	
052	Ki Loi	174181	981380	4000	07/08/91	
053	Mae Long	174142	981689	5000	04/29/91	
054	Mae Lan	174153	982112	3500	07/08/91	
055	Yang Piang	174519	982742	3550	06/21/91	12/26/92
061	Se Kra	173138	981178	2850	01/22/91	
062	Khun Song	173365	981684	3800	09/29/91	
063	Chok Pok	173406	982116	3175	07/08/91	
064	Sop Hat	173400	982600	2100	07/08/91	
071	To Che	172990	981125	2400	01/22/91	
072	Mo Doe Khi	172916	981709	2600	07/09/91	
073	Kha Nun	172883	982134	4500	07/09/91	
074	Nang Non	172900	982800	1600	06/22/91	
081	Wa Bop Khi	172564	981527	2850	07/09/91	
082	I Pho Khi	172491	982035	4290	03/16/91	
083	Ton Bin	172521	982661	1100	07/09/91	
084	Mon Chong	172496	982962	1700	07/09/91	
091	Tako Khi	172041	981460	2300	01/23/91	
092	Loe To	172070	982125	3450	07/22/91	
093	Nam Yen	171771	982540	3000	07/09/91	
094	Phra Bat	171880	982431	4050	07/09/91	

Table 11.1. - AARRP rain gauge site list continued (lat. and long. given in degrees and hundredths of minutes).

Station No.	Name	Location Lat. N	Long.E	El. (ft)	Start mm/dd/yy	End mm/dd/yy
095	Mining	172040	983028	1100	07/09/91	
101	Ta Po Pu	171600	981000	1700	06/03/92	04/16/93
102	Ton Ngiu	171534	982510	2200	04/18/91	04/16/93
103	Pae Poe	171622	982984	1450	01/24/91	04/16/93
311	Fai Noi	182010	993301	1030	04/23/92	
312	Pu Ling	173047	982953	2530	04/04/92	
321	Chiang Mai	184620	985839	1250	04/27/92	
322	Mae Bon	170653	990501	0700	04/24/92	
323	Nam Mae Li	175330	990513	1450	04/22/92	
324	Pha Daeng	164960	990802	0530	04/24/92	
325	Sop Tear	182383	984081	0540	04/17/92	
331	Dam Site	171404	990342	0200	04/23/92	
332	Serm Ngarm	180467	991428	0790	04/22/92	
333	Li	175182	990205	0850	04/22/92	
334	Wang Lung	181066	983670	0840	04/17/92	
335	Mae Khan	183175	985137	0940	04/17/92	
336	Huay Bong 2	180901	982562	2944	04/24/93	
343	Koh Ka	181254	992505	0630	04/23/92	
344	Mae Rim	190033	985664	0910	04/25/92	
345	Mae Lop	174958	981154	4150	05/05/93	
355	Na Fon	180851	982171	3650	04/24/93	
401	Mae Lai	180287	982181	3450	04/24/93	

Table 11.2. - Available data periods for AARRP rain gauge stations.

Stn. No.	1991	1992	1993
001	06/24 - 12/31	01/01 - 07/17	04/18 - 08/10
		08/21 - 12/31	
002	06/24 - 12/31	01/01 - 12/31	04/18 - 08/10
003	06/24 - 12/31	01/01 - 12/31	04/18 - 08/10
011	07/08 - 12/31	moved 04/05	
012	06/07 - 12/31	moved 04/04	
013	06/08 - 12/31	01/01 - 12/31	05/05 - 08/10
021	07/08 - 12/31	moved 04/05	
022	08/31 - 12/31	moved 04/05	
023	04/29 - 12/31	moved 04/05	
024		moved 04/06	
025	06/07 - 12/31	moved 04/04	
031	no data	moved 04/05	
032	04/29 - 12/31	moved 04/05	
033	07/07 - 09/13	moved 04/05	
034	07/07 - 12/31	moved 04/04	
035	06/07 - 12/31	moved 04/05	
036	06/08 - 12/31	04/11 - 12/31	moved 04/13
041	problem site	moved 09/19	
042	04/29 - 07/30	01/01 - 12/29	05/22 - 08/26
	09/24 - 12/31		
043	09/13 - 12/31	removed 04/05	
044	07/07 - 12/31	removed 04/06	
045	06/21 - 12/31	01/01 - 12/31	moved 04/02
046	06/08 - 12/31	07/07 - 09/05	01/01 - 08/13
		10/24 - 12/31	
051	04/29 - 12/31	01/01 - 12/31	04/14 - 08/26
052	07/08 - 12/31	01/01 - 12/31	04/14 - 08/26
053	no data	no data	04/16 - 08/26
054	07/08 - 12/31	01/01 - 07/07	01/01 - 08/26
		08/20 - 12/31	
055	06/21 - 12/31	04/16 - 07/30	moved 04/02
		08/19 - 12/26	
*061		01/17 - 12/31	01/01 - 08/15
062	09/29 - 12/31	05/03 - 12/31	01/01 - 08/26
063	07/08 - 12/31	01/01 - 12/31	01/01 - 08/26
064	07/08 - 12/31	05/03 - 12/31	01/01 - 08/26
071	09/29 - 12/31	05/03 - 07/30	01/01 - 08/26
		08/27 - 12/31	
*072	07/09 - 12/31	questionable data	04/15 - 08/26
073	07/09 - 12/31	01/01 - 12/31	01/01 - 06/04
			07/02 - 08/26
074	06/22 - 12/31	04/11 - 12/31	01/01 - 06/05
			07/03 - 08/13

* remove and relocate rain gauge

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Table 11.2. - Thailand rain gauge data available data periods for AARRP rain gauge stations - continued.

Stn. No.	1991	1992	1993
081	07/09 - 11/28	06/03 - 12/25	04/15 - 08/27
082	03/16 - 10/16	05/13 - 12/31	01/01 - 08/27
*083	07/09 - 12/31	01/01 - 12/31	01/01 - 08/27
084	07/09 - 12/31	01/01 - 12/31	01/01 - 08/27
*091		01/01 - 12/31	01/01 - 08/27
092	07/22 - 12/31	01/01 - 12/31	04/14 - 08/27
093	07/09 - 12/31	01/01 - 12/31	04/14 - 08/27
*094	07/09 - 12/28	questionable data	04/14 - 07/02
*095	07/09 - 12/31	01/01 - 08/16	06/05 - 08/27
		08/19 - 12/31	
101		06/03 - 12/31	moved 04/16
102	10/03 - 12/31	01/01 - 12/31	moved 04/16
103	01/07 - 12/31	06/01 - 12/31	moved 04/16
311		04/23 - 12/31	04/20 - 08/15
312		04/04 - 12/31	04/25 - 08/13
321		04/27 - 12/31	04/20 - 08/15
*322		04/24 - 12/31	04/23 - 07/04
323		04/22 - 12/31	04/20 - 08/15
*324		04/24 - 12/31	04/23 - 07/04
325		04/17 - 12/31	04/21 - 08/16
*331		04/23 - 11/09	04/23 - 07/04
332		04/22 - 12/31	04/20 - 05/31
			06/18 - 08/15
333		04/22 - 12/31	06/11 - 08/15
334		04/17 - 12/31	04/20 - 08/16
335		04/17 - 12/31	04/21 - 08/16
336			04/24 - 08/10
343		04/23 - 12/31	04/20 - 08/15
344		04/25 - 12/31	04/20 - 08/16
345			05/05 - 06/04
			06/28 - 08/26
355			04/24 - 06/06
			06/13 - 08/10
401			04/24 - 06/06
			06/28 - 08/10

* remove and relocate rain gauge

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12. THE DATA COLLECTION AND MANAGEMENT PROGRAM

12.1 Introduction

The establishment of a viable data management program is a basic and vital component of the AARRP. How the data collected in support of the AARRP are managed will govern the timing and accuracy of the demonstration project design and evaluation and, therefore, the success in developing and implementing a proven rainmaking technology for Thailand. Two individuals, the AARRP Data Manager and the AARRP Data Archivist, are responsible for establishing and overseeing the AARRP data management program.

The *AARRP Data Manager*, located at the AARRP Field Operations Center in Chiang Mai, is responsible for ensuring that all AARRP data are routinely collected, quality controlled, inventoried, and transported to the AARRP Data Archivist at RRRDI in Bangkok. Duties of the AARRP Data Manager include the following:

1. Work with the scientists/technicians responsible for each type of AARRP data collected in the field to develop schedules and checklists for the collection and quality control of the data; ensure that the schedules are maintained and checklists are properly completed.

2. Develop an "equipment problem report" computer file on a PC located at the Field Operations Center; ensure that the information in this file is kept current.

3. Develop a filing system at the Field Operations Center for filing all AARRP data collected each day during the field season.

4. Work with the AARRP Data Archivist to develop AARRP data inventory/transmittal checklists.

5. Periodically, make AARRP data shipments to RRRDI in Bangkok; ensure that each shipment is accompanied by a data transmittal checklist for each data type.

6. Following each field season, assist the AARRP Data Archivist in the preparation of an "AARRP Data Inventory" document.

The *AARRP Data Archivist*, located at RRRDI in Bangkok, is responsible for ensuring that all required data are routinely assembled, inventoried, archived, and made accessible to project scientists for subsequent analysis. Duties of the AARRP Data Archivist include the following:

1. Develop and maintain data documentation files on a PC located at the RRRDI Computer Center.

2. Work with the AARRP Data Manager to develop AARRP data inventory/transmittal checklists.

3. Upon receipt of each AARRP data shipment at RRRDI in Bangkok, compare the transmittal list(s) against the data records received to ensure that no data are missing and that the data are properly documented.

4. Develop and maintain a comprehensive data inventory on a PC located at the RRRDI Computer Center.

5. Arrange for the collection, processing, and quality control of non-project data which are needed for AARRP design and evaluation studies.

6. Make copies of: 1) all AARRP radar data tapes, 2) AARRP radar operations logs, 3) all rain gauge data diskettes, and 4) rain gauge servicing logs; prepare an inventory and mail to NASA in the U.S.

7. Develop and maintain a data archival system to ensure safe storage of data records.

8. Annually, oversee the preparation of an "AARRP Data Inventory" document; this document should include a summary of the types of data available to requestors and the procedures for requesting the data.

The AARRP data management program requires effective and coordinated procedures that address the following data handling activities:

- Sources
- Collection
- Documentation
- Quality Control
- Inventory
- Archival
- User Accessibility
- Software

12.2 Data Sources

The types of data available for use in evaluating the demonstration project, the locations of the observation sites, and the sources of the data should be identified. Two categories of data sources exist, project and non-project.

1. Project data sources refer to data collected directly by AARRP measurement systems. These include:

    a) Radar data from the AARRP radar site near OmKoi.
    b) Aircraft and cloud physics data from the AeroCommander 690B high altitude cold cloud seeding aircraft.
    c) Rawinsonde data from the AARRP radar site and the field research center (TMD weather station at Chiang Mai).
    d) Precipitation data from the AARRP rain gauge network.
    e) Satellite data from the remote satellite computer display/recorder system at the AARRP Radar Site.
    f) Weather maps and charts used at the AARRP Field Operations Center.
    g) Operations logs maintained by the Field Operations Director and measurement system coordinators, including type of experimental day, aircraft and radar operations times, aircraft seeding times, types and amounts of materials released, system calibrations, etc.

2) Non-project data sources refer to data collected by non-AARRP organizations that are needed for the design and evaluation of the demonstration project. These include:

   a) Hydrological data from EGAT (Electricity Generating Authority of Thailand) and RID/Stream Gauges.
   b) Surface, upper air, and rainfall (especially 24-hour totals) data from the TMD for all synoptic weather stations and supplementary sites within 150 kilometers of the AARRP radar near OmKoi.
   c) Aircraft track data from the Doi Ithanon Air Force radar.

12.3 Data Collection

Systematic data collection procedures must be established for obtaining data from all project and non-project sources on a routine schedule. The AARRP Data Manager, located at the Field Operations Office at Chiang Mai, shall work with the AARRP staff assigned to each type of project data generating system to develop routine procedures and schedules for collecting the data. The AARRP Data Archivist at RRRDI in Bangkok shall arrange to obtain the required non-project data from their respective sources as soon as they become available.

The AARRP Data Manager and Data Archivist shall work together to establish a schedule for AARRP data shipments from the Field Operations Center to RRRDI in Bangkok, and to develop an AARRP data inventory/transmittal checklist for each type of data. The data transmittal checklists shall include the following information:

1. Type of data collected and individual(s) who collected the data.
2. Data collection time period, including start/stop time of each record.
3. Description of data problems found during the data quality control checks, and individual(s) who checked the data records.
4. Comments on equipment performance and maintenance, especially calibration data.

The Data Manager has the responsibility to ensure that each data shipment from the Field Operations Center to RRRDI in Bangkok includes filled out checklists for each type of data. Upon receipt of the data shipment at RRRDI in Bangkok, the AARRP Data Archivist shall check the transmittal checklists against the data records received to ensure that no data are missing and that the data are properly documented.

12.4 Data Documentation

All types of data that are collected shall be documented on a PC by the AARRP Data Archivist. The data base files should include a subfile that contains the following information for each parameter from each data source:

1. Individual(s) responsible for collecting the data and making quality control checks of the data records.
2. Type of parameter recorded/observed.
3. Medium of original data record, e.g., tape, diskette, map, etc.
4. Frequency of observation.
5. Units of measure.
6. Location of observation site(s).
7. Site exposure characteristics and changes, if any.

8. Type of equipment and changes, if any.
9. Calibration record, including sensor accuracy.
10. Schedule for data collection.
11. Storage medium for processed data, e.g., diskette or tape, and labeling format.
12. Storage location for original data records and processed data.
13. Format for archived data.
14. Software available to process, display, or analyze the data.
15. Key personnel who know most about the data.

This subfile should be updated as necessary to record any changes; however, the changes should be additions and not replacements so that a data history is developed for each parameter.

12.5 Data Quality Control

The Data Manager has the responsibility to ensure that a good quality control program is in place for AARRP data. Consequently, this individual shall monitor and coordinate all AARRP data quality assurance activities. The scientists or technicians responsible for the collection of each type of data shall quality control the data records to check the functioning of instruments and the reasonableness of the data being recorded. The AARRP data quality control process shall be implemented in two steps, first to identify equipment and data collection problems, and second to identify any problems with the data. The first step shall be performed as soon as possible after collecting a data record in the field. The Data Manager shall develop and maintain an "equipment problem report" file on a PC, which documents a problem, records an appropriate response, and resides in a suspense file until the problem is resolved. Data problems identified during the second step will usually require human judgement to resolve.

In the non-project data processing and quality control tasks at RRRDI by the AARRP Data Archivist, data reduction shall be standardized and, if appropriate, computerized. However, the initial data reduction and entry for some data will be done by hand. To eliminate errors, all data records initially reduced by hand should be done independently by two individuals and compared.

Each type of data will require a specific set of quality assurance checks. When feasible, both AARRP and non-project processed data will be entered into computer files at RRRDI. These data should undergo additional quality control by computer checks. For example, rainfall data from rain gauges should be screened to ensure that storm accumulations relate to correct dates at all sites, and that they are reasonably consistent with each other. Other quality checks will require human judgment to resolve.

12.6 Data Inventory

The data management system should be used to compile and maintain a data inventory. The inventory for each data type should include:

1. Date of original data records received at Data Management Center.
2. Name of individual who collected data.
3. Starting and ending dates/times of the data record.
4. Scientist/technician who performed data quality control.

5. Completeness of data; identification of all missing data.
6. Equipment performance/maintenance record.

As soon as possible after each field season, an "AARRP Data Inventory" document shall be issued by the AARRP Data Manager and Data Archivist. This document shall, as a minimum, contain copies of updated data source documentation and the data inventory described above. The document should also state the types of data available to requestors and the procedures for requesting the data.

12.7 Data Archival

The responsibility for proper data archival rests with the AARRP Data Archivist. Data should be stored in environmentally safe locations that are suitable for each type of data, e.g., numbered file cabinets, diskette storage containers, tape racks, etc. Safeguards against catastrophic loss should be in place. Data should be duplicated whenever possible and the backup copies should be kept at a separate location from the original data. The original copies of data should not leave their stored locations except under special or unusual circumstances.

12.8 Data Accessibility

The AARRP Data Archivist, in cooperation with the MicroVax Systems Manager, shall develop procedures that allow for simple data retrieval for analysis purposes while maintaining data security. The data management system shall be used to maintain a Data Checkout File for non-computerized data. The Data Checkout File shall contain information on what data are checked out, who checked the data out, where the data are being used, and when the data will be returned to the data archive. The Data Checkout File should be used even when copies of data are provided that do not have to be returned.

12.9 Data Software

All computer programs that have been developed or are being developed to process, quality control, inventory, display, or analyze data shall be documented, including the author's name, by the MicroVax Systems Manager. This information shall be included in the documentation for each data source/type. The purposes of this documentation are to make these programs available to all data analysts and to eliminate duplication of software development.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.

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