R-89-10

APPLIED ATMOSPHERIC RESOURCES RESEARCH PROGRAM IN THAILAND

INTERIM SCIENTIFIC REPORT

SUBMITTED TO
U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

UNDER ANE-0337-P-IZ-8021-00

August 1989

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
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16. ABSTRACT The Royal Thai Government requested assistance of the United States Agency for International Development for the development and implementation of a more comprehensive scientific approach to the design, operation, and evaluation of Thailand's weather modification program. Upon visiting Thailand, a team of American scientists recommended a 5-year developmental program to improve Thai technical capabilities through training, additional equipment, and a demonstration cloud seeding project. A core training course was conducted in Thailand in early 1988. A study of the scientific concepts underlying the Thailand program was performed using one-, two-, and three-dimensional cloud models, some adjusted to simulate cloud seeding to test various cloud treatment scenarios for the demonstration program. This program will test for an increase in rainfall from (1) warm clouds seeded with hygroscopic agents and (2) cold clouds seeded for dynamic effects with glaciogenic materials. Cloud model runs produced encouraging results for both cloud types, so a preliminary design has been developed for the demonstration project. The field prgram will be conducted in the Nam Mae Tun River Watershed of western Thailand. Field equipment and support will include cloud seeding aircraft, a 10-centimeter Doppler radar with dual polarization, an operations center for weather forecasting and monitoring, and a rain gauge network. A randomized crossover design is proposed with the experimental unit, the assemblage of clouds affecting a randomly selected target area over 3 hours. The primary response variable is rainfall measured by rain-gauge-adjusted radar. Analyses indicate that rainfall occurs on about 90 days per wet season and, if seeding yields 10 percent increases, about 90 experimental units are required per stratification to achieve a 90-percent probability-of-detection at a significance level of 0.05. Given equal numbers of warm and cold cloud units and typical operations problems and weather variability, at least four seasons of field experimentation are required.

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by

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SI METRIC

August 1989

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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EXECUTIVE SUMMARY

Since the late 1960's, under the direction of His Majesty King Bhumipol Adulyadej, scientific and technical organizations in the Kingdom of Thailand have been involved with the design and implementation of a series of experiments and operational programs to increase rainfall through weather modification. A national program of weather modification was formalized in 1975 through the establishment of the RRRDI (Royal Rainmaking Research and Development Institute) under the MOAC (Ministry of Agriculture and Cooperatives).

Recognizing the need for a more comprehensive scientific approach to the design, operation, and evaluation of Thailand's weather modification program, His Majesty requested assistance from the United States Agency for International Development (USAID). This request resulted in an interdisciplinary team of four American scientists visiting Thailand during September 1986 to assess the requirements and the resources available for weather modification activities in the country.

The team of scientists recommended a 5-year developmental weather modification program to improve the technical capabilities of the RRRDI through training, additional equipment, and a demonstration cloud seeding project. The ultimate goal of the demonstration was to increase manageable water resources by implementation of improved technology in Thailand's cloud seeding operations.

USAID agreed to fund the 5-year program, and a PASA (Participating Agency Service Agreement) was signed between USAID and the Bureau of Reclamation to support the work. This interim progress report describes the initial stages of the work, which included (1) provision of a core training course in Thailand on cloud physics and weather modification, (2) study of the scientific concepts underlying the RRRDI program, and (3) design of a demonstration project capable of determining the effectiveness of cloud seeding in Thailand. In addition to providing a summary of progress on these three items, this report provides a number of recommendations designed to speed progress toward the overall objectives of the program.

The core training course was conducted in February and March 1988. A total of 41 persons registered for the course, which was intended as a first step in technology transfer. Course objectives were to acquaint participants with the scientific principles, terminology, and technology of weather modification. A number of lecturers presented material, each in his respective specialty. The services of two professors of meteorology and atmospheric science at American universities were provided under contract. The other lecturers were Reclamation employees. In order to overcome language difficulties, the Royal Thai Government provided 12 facilitators who presented written and oral lecture summaries and were available to answer questions. Course evaluations completed by the attendees indicated that the presentation was a success.

The study of the scientific concepts underlying the RRRDI program was carried out using cloud models. The models employed predicted the location and extent of cloud development. The orographic influence of Thailand mountains on cloud initiation and growth was well depicted. By accounting for important microphysical and dynamic cloud processes, the models predicted cloud evolution, including precipitation development. Models were adjusted to reflect cloud seeding; consequently, various cloud treatment scenarios were tested.

The two basic cloud seeding concepts to be tested in Thailand are (1) the increase of the rain by coalescence of liquid droplets; and (2) the treatment of cumulus clouds to produce dynamic effects, including increases in cloud size and lifetime and, consequently, rainfall production. The most common way to induce dynamic effects in clouds is to seed supercooled clouds with ice-forming agents, thereby releasing latent heat. Both seeding concepts were tested with various numerical cloud models using available Thailand upper air meteorological data and descriptions of principal terrain features as input.

The cloud model runs indicated that hygroscopic seeding of many relatively warm clouds in Thailand should lead to precipitation increases. In addition, the model runs indicated that seeding of some cold clouds (clouds with temperatures well below 0 °C at their tops) would produce dynamic effects that could lead to additional rainfall. Dynamic effects were indicated for about 35 percent of the operational days on the RRRDI program.

Preliminary design work on the demonstration project extended beyond the numerical studies of possible responses to seeding. After visiting potential experimental sites, officials of the RRRDI and Reclamation selected the Nam Mae Tun River area of western Thailand for conduct of the demonstration project. According to present plans, the project office will be located at the Bhumipol Dam site, and a weather radar will be installed about 9 kilometers east of Omkoi on a ridge which will provide a good view of the Nam Mae Tun River drainage. The operations center will be equipped to obtain necessary data for weather forecasting and monitoring.

Cloud seeding aircraft outfitted for hygroscopic and glaciogenic seeding will conduct the cloud treatment. Plans are to equip one seeding aircraft for meteorological data collection, including some basic measurements of cloud microphysics. A 10-centimeter weather Doppler radar and a network of rain gauges will collect data for physical and statistical evaluation. The radar will have doppler and polarization capabilities. The radar data will be used to refine rainfall estimates and for advanced cloud physics studies.

Two target areas, each of about 700 km^2, have been tentatively selected for conducting the demonstration project. For each experimental unit, one experimental area will be selected at random for treatment and the other will serve as a control for that unit. Estimates of rainfall in the target areas will be based primarily on radar observations adjusted on the basis of point observations by rain gauges.

Historical data from the project area indicate that, on the average, rainfall occurs on about 100 days of the wet season from May through October, inclusive, presenting potential experimental cases. Simulations indicate that about 90 cases per statistical stratification will be required to provide a 90-percent probability of detecting a 10-percent increase in rainfall at a significance level of 0.05. Analyses suggest that, given typical equipment problems and weather variability, at least four seasons of experimentation will be necessary to obtain significant results.

It is recommended that theoretical and related field studies be conducted of Thailand weather and clouds. Some of these studies should be conducted prior to the commencement of randomized seeding since the information sought is important to refining and finalizing the project design. Preliminary studies of particular importance are those related to better defining cloud seeding potential. Recommended preliminary studies are discussed in section 5 and appendix B of this report. Other studies will be recommended after preliminary data analysis takes place and the design is finalized. Information developed in these studies will be helpful in understanding the physical processes of Thailand clouds and in interpreting the results of the statistical and physical evaluations.

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GLOSSARY

AARRP . . . . Applied Atmospheric Resources Research Program
AgCl . . . . silver chloride
AgI . . . . silver iodide
AVHRR . . . . advanced very high resolution radiometer
CCL . . . . convective condensation level
CRAY . . . . brand name of a supercomputer
CRG . . . . Silverman's graupel formation process of coalescence, freezing, then riming
CTT . . . . cloud top temperature
dBZ . . . . a logarithmic scale of radar measurement intensity
EGAT . . . . Electricity Generating Authority of Thailand
GMS . . . . geostationary meteorological satellite
HIPLEX . . . . High Plains Cooperative Program
IFF . . . . device to locate aircraft by radar
IRG . . . Silverman's graupel formation process of ice crystal growth by vapor diffusion then riming
mb . . . . millibar, a unit of atmospheric pressure
MESOCU . . . . . . a specific one-dimensional, steady-state cloud model that uses bulk microphysics
MOAC . . . . Ministry of Agriculture and Cooperatives
MRPP . . . . multiresponse permutation procedures
NCAR . . . . National Center for Atmospheric Research
NOAA . . . . National Oceanic and Atmospheric Administration
PASA . . . . Participating Agency Service Agreement
RRRDI . . . . Royal Rainmaking Research and Development Institute
SLW . . . . supercooled liquid water
VAX . . . . brand name of a minicomputer
VOR/DME . . . . . equipment on aircraft used for location of aircraft with respect to a known site
WMO . . . . World Meteorological Organization
Z_{DR} . . . . differential reflectivity

1. INTRODUCTION AND BACKGROUND

Since the late 1960's under the direction of His Majesty King Bhumipol 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 through establishment of the RRRDI under the MOAC in 1975. The principal objective has been to increase the rainfall in the important agricultural areas of Thailand, where rainfall in some years is less than optimal for crop production.

Throughout the years, the RRRDI officials responsible for the Thailand weather modification program have attempted to improve its effectiveness by taking advantage of recent scientific findings. The RRRDI cooperates with the World Meteorological Organization and 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. Personnel from RRRDI made official visits to the People's Republic of China in 1984, to the United States in 1985, and to Canada in 1986.

Recently 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. In response, the Royal Thai Government requested assistance of USAID, who agreed to sponsor a visit by a team of experts to assess the RRRDI program and make suggestions for improvements. USAID entered into a PASA with the Bureau of Reclamation for implementation of the Thailand weather modification assessment. The PASA to finance the assessment received final signature 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 the Bureau 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 the RRRDI program and discussed weather modification technology with many members of the Royal Thai Government concerned with water development and agriculture. On September 21, 1986, the team members had an audience with His Majesty the King, who provided his views concerning desirable future programs within RRRDI. Details concerning the team visit as well as background information on the climate of Thailand and the history of weather modification in that country 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 technical capabilities of the RRRDI through training; additional equipment, including computers and meteorological sensors; and a demonstration cloud seeding project. USAID accepted in principle the recommendation for a broad-based program to upgrade the capability of RRRDI and related groups within MOAC. This broad-based program is known as the AARRP (Applied Atmospheric Resources Research Program). The original PASA was amended to provide for continued program planning studies through a visit to Thailand in the summer of 1987 by Dr. Silverman and another Reclamation scientist, Dr. Roy M. Rasmussen. Further negotiations among Reclamation, USAID, and the Royal Thai Government led to a second PASA, the current one, between Reclamation and USAID to support the proposed AARRP. Signing of the current

PASA, under which this interim report is submitted, was completed on April 8, 1988. According to language in the PASA,

> "The goal of the program is to increase manageable water resources in Thailand through the implementation of a scientifically based weather modification project performed 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, from a scientific and economic standpoint, of long-term weather modification application as a water resources management technique in Thailand . . . The project design includes both short-term measures that will assist and improve present operations and the development of a long-term program to enhance national water supplies."

The Project Implementation Plan and Schedule of the current PASA calls for work organized generally along the lines suggested by Silverman et al. (1986). The initial fund obligation was intended to support mainly the following technical activities: (1) evaluation of scientific seeding concepts potentially applicable in Thailand, (2) provision of a core training course in Thailand on cloud physics and weather modification, (3) design of a demonstration project to determine the effectiveness of weather modification by cloud seeding in Thailand, and (4) preparation of specifications for AARRP equipment. Under a preincurred costs clause, work actually began in advance of the signing of the PASA. In particular, the core training course was completed in March 1988.

In accordance with the terms of the current PASA, this interim report provides an overview of the scientific concept evaluation studies and the demonstration project design, and an assessment of the training course, which was officially named the Atmospheric Water Resources Management Symposium. Equipment specifications were completed and sent to USAID and RRRDI in July 1988.

Section 2 of this report provides a brief description of the symposium and an assessment of its usefulness to the Thai personnel in attendance. Section 3 gives background information on the scientific concepts that have guided the RRRDI program to this point and describes the cloud model runs and other studies made by Reclamation under the current PASA to refine and extend those concepts. Section 4 gives a design for the demonstration program, which is based in part on the results of the studies described in section 3. Appendix A provides some details on the types of cloud models used to assess seeding concepts and additional information on the results of the various model runs that were made. Appendix B describes some additional studies that should be done before the demonstration project goes into the field.

2. ATMOSPHERIC WATER RESOURCES MANAGEMENT SYMPOSIUM

2.1 Objectives and Organization

As a part of the activity under the PASA, Reclamation provided a core training course in theoretical and applied cloud physics and weather modification for Thai personnel. The training course was officially named the Atmospheric Water Resources Management Symposium. The symposium was given at Chiang Mai from February 9 to March 11, 1988. The facilities for the symposium were arranged for and supervised by the Technical Working Group for the 5-Week Core Training, which served as the implementation arm of the subcommittee for the 5-Week Core Training. The Technical Working Group and Subcommittee were chaired by Mrs. Subongkot Jamikorn and Dr. Archampon Khumbanonda, respectively.

A list of the 41 persons registered for the symposium is given in table 2.1. A measure of the importance attributed to the symposium by Thai officials is the fact that several persons from universities and Royal Thai Government agencies other than RRRDI registered and attended the lectures.

The symposium was intended as a first step in technology transfer. The objectives were to acquaint course participants with the scientific principles and components of weather modification as a water augmentation tool and with its terminology and technology, including new tools for observing the atmosphere. The intent was not that the participants would graduate as weather modification experts; but that they would be placed in a good position to benefit from the more advanced training, including university courses and in-service training, that will be provided in the future. In setting up the symposium, Reclamation decided to make use of several lecturers. This decision was made so that each topic included in the symposium could be covered by an outstanding expert in that area of specialization. The services of two such experts were obtained under contract - Professor Harold Orville of the South Dakota School of Mines and Technology lectured on numerical cloud modeling, and Professor Gabor Vali of the University of Wyoming lectured on cloud physics. The other American lecturers were all members of the Reclamation staff. A list of the American lecturers is given in table 2.2.

As the seminar participants were not given English language training in preparation for the symposium, it was anticipated that some of them would have difficulties with some of the lectures. As a partial solution to this problem, the Technical Working Group for the 5-Week Core Training provided 12 distinguished Thai facilitators (table 2.3). At the conclusion of each lecture, a facilitator presented a verbal summary of that lecture in Thai. Facilitators also prepared a written summary of each lecture in Thai, which was provided to each participant as a supplement to the extensive lecture notes and textbooks distributed by the American lecturers. In addition, facilitators worked with the participants in the evenings, reviewing the material that had been presented in the lectures.

The subject matter presented covered a wide spectrum of topics relevant to weather modification projects. The topics included (a) cloud physics, (b) cloud modeling, (c) review of previous projects, (d) types of instrumentation available for use on aircraft and on the ground, (e) project design and evaluation, (f) weather forecasting, (g) data management, (h) economic considerations, (i) societal and environmental concerns, (j) scientific planning and project management, (k) the Thailand drought warning study, and (l) the 5-year plan of the RRRDI. Table 2.4 lists the topics covered and the lecturer(s) for each session of the symposium. There was some intentional overlap among the lecturers. In general, each lecturer observed presentations by other lecturers and the manner in which the symposium was being conducted for a day before speaking at the symposium. As only 5 weeks were scheduled to cover the extensive subject matter, the presentations had to focus on the most important aspects or highlights of each topic. Detailed coverage was necessarily left to possible future and more extensive training activities.

As noted above, the topics covered in the symposium included the use of numerical cloud models to study cloud dynamics and cloud physics processes. Cloud models, which are capable of simulating such complex phenomena as entrainment of ambient air into cumulus clouds and the release of latent heat when cloud droplets freeze, are the most satisfactory way to approach the subject of cloud dynamics. A special lecture in Thai on cloud modeling was given on February 27 by Dr. Patipat Patvivasiri of the Thai Meteorological Department to supplement the presentations by Drs. Orville and Rasmussen. Some of the lecturers brought personal computers to Thailand, and some additional computers were leased in Thailand so that the symposium participants could have first-hand experience in running some of the simpler models. This aspect of the course was gratifying to the participants and helped them master quickly the use of cloud models to interpret the behavior of actual clouds. The personal computers also proved very useful in performing statistical procedures used in evaluation of results of weather modification projects.

Table 2.1. - Names and affiliations of registrants in the Atmospheric Water Resources Management Symposium

Organization	Name
Royal Rainmaking Research and Development Institute	Ms. Angkana Surapongpairush
	Mr. Anupap Pavavathananusorn
	Mr. Arkhanay Boonlert
	Ms. Boonrueng Songcharean
	Mr. Chamroen Suntudthikun
	Ms. Iracha Boonlert
	Mr. Kiattisak Thangtrongsakol
	Mr. Kwanchai Tawamongkol
	Ms. Maneewan Tisara
	Mr. Noppadol Boonyachalito
	Mr. Padungchit Korawis
	Mr. Panithi Samerwong
	Mr. Prasert Auangsuratana
	Mr. Prinya Sudhikoses
	Mr. Prede Thongkum
	Mr. Preecha Bun-o-pars
	Ms. Rachaneewan Talumassawatdi
	Mr. Ratana Ratanamalaya
	Mr. Saneh Warit
	Mr. Somchai Ruangsuttinarupap
	Mr. Sommart Daengchai

Table 2.1. - Names and affiliations of registrants in the Atmospheric Water Resources Management Symposium - Continued

Organization	Name
Royal Rainmaking Research and Development Institute (Cont.)	Mr. Song Klinpratoom Ms. Sukanya Srakaew Mr. Tawee Kanchana Ms. Wantana Samerwong Mr. Warawut Khantiyanan Mr. Wathana Sukarnjanaset Mr. Wera Phaphuangwittayakul
Agricultural Aviation Division, MOAC	Mr. Chamlert Pattanodomm Mr. Sangob Suvansang
EGAT (Electricity Generating Authority of Thailand)	Mr. Sopon Jariyasuwan Mr. Worapoj Worapong
Royal Thai Army Chemical Department	Lt. Anuchit Boonyapattipark Maj. Grisana Tongsumrit Lt. Col. Vimon Ngaopisadarn
Dept. of Meteorological Services	Ms. Angkna Pyomjamsri
Chulalongkorn University	Dr. Sutat Weesakul
Kasetsart University	Ms. Anongnart Srivihok Ms. Viyada Busyanond
Chiang Mai University	Mr. M. L. Aniwat Sooksawat
Srinakharinwirot University	Dr. Suwanna Panturat

Table 2.2. - List of American lecturers in the Atmospheric Water Resources Management Symposium

Dr. Bernard A. Silverman Bureau of Reclamation U. S. Department of the Interior	Ph.D. (Geophysical Sciences)
Dr. Gabor Vali Department of Atmospheric Science University of Wyoming Laramie, Wyoming	Ph.D. (Physics)
Dr. Harold D. Orville Department of Meteorology South Dakota School of Mines and Technology Rapid City, South Dakota	Ph.D. (Meteorology)
Dr. Roy M. Rasmussen Bureau of Reclamation U. S. Department of the Interior	Ph.D. (Atmospheric Sciences)
Mr. Jonnie G. Medina Bureau of Reclamation U. S. Department of the Interior	M.S. (Statistical Meteorology)
Mr. David W. Reynolds Bureau of Reclamation U. S. Department of the Interior	M.S. (Atmospheric Science)

Table 2.3. - List of facilitators in the Atmospheric Water Resources Management Symposium

Mr. Sommai Surakul Deputy Permanent Secretary Ministry of Agriculture and Cooperatives	
Assoc. Professor Dr. Anek Hirunraks Dept. of Biostatistics Faculty of Public Health Mahidol University	Ph.D. (Statistics)
Asst. Professor Ms. Subongkot Jamikorn Dept. of Statistics Faculty of Science Kasetsart University	M.S. (Economic Statistics)
Assoc. Professor Dr. Prungjun Wongviset Faculty of Industrial Education and Sciences King Mongkut's Institute of Technology	Ph.D. (Mathematics)
Asst. Professor Dr. Jiemjai Kreasuwan Dept. of Physics Faculty of Sciences Kasetsart University	Ph.D. (Atmospheric Science)
Asst. Professor Dr. Rong Rujkorakarn Dept. of Physics Faculty of Sciences Khon Kaen University	Ph.D. (Physics)
Asst. Professor Dr. Thanawat Aimsomboon Srinakharinwirot University	
Asst. Professor Dr. Suradaj Thavornpithak Dept. of Statistics Faculty of Sciences Khon Kaen University	M.Sc. (Applied Statistics)
Asst. Prof. Dr. Dajawut Nitayasuthi Dept. of Biostatistics Kasetsart University	M.Sc. (Medical Statistics)
Dr. Nunta Vanichsetakul Dept. of Statistics Faculty of Sciences Kasetsart University	Ph.D. (Statistics)
Dr. Apichart Pongsrihadulchai Center for Agricultural Statistics Ministry of Agriculture and Cooperatives	Ph.D. (Economics)

Table 2.3. - List of facilitators in the Atmospheric Water Resources Management Symposium - Continued

Dr. Chitpong Chaiwasu Faculty of Medicine, Ramathibodi Hospital Mahidol University	Ph.D. (Microbiology)

Table 2.4. - Topics covered and lecturers for Atmospheric Water Resources Management Symposium

Date/Session	Topic	Lecturer
February 9		
a.m.-1	Chairman of the opening ceremony	Mr. Pong Sono Deputy Permanent Secretary, MOAC
	Welcoming remarks	Mr. Phet Khumsone Deputy Governor, Chiang Mai
		Mr. Charles S. Ahlgren U. S. Consulate General, Chiang Mai
		Dr. Bernard A. Silverman Bureau of Reclamation
	Report by Chairman of the Subcommittee for the 5-Week Core Training	Dr. Archampon Khumbanonda
	Opening of the Symposium	Mr. Pong Sono
p.m.-1	Applied Atmospheric Resources Research Project	Dr. Anek
p.m.-2	World view of precipitation enhancement	Dr. Silverman
February 10		
a.m.-1	Cloud and precipitation types	Dr. Vali
a.m.-2	Cloud droplet and ice particle populations	Dr. Vali
p.m.-1	Precipitation from warm clouds: observations	Dr. Vali
p.m.-2	Precipitation from warm clouds: models	Dr. Vali
February 11		
a.m.-1	Ice-phase precipitation: observations	Dr. Vali
a.m.-2	Ice-phase precipitation: models	Dr. Vali
p.m.-1	Cloud-scale and mesoscale organization	Dr. Vali
p.m.-2	Precipitation enhancement hypotheses: coalescence growth	Dr. Vali
February 12		
a.m.-1	Precipitation enhancement hypotheses: increasing ice concentrations	Dr. Vali
a.m.-2	Precipitation enhancement hypotheses: stimulating cloud growth	Dr. Vali

Table 2.4. - Topics covered and lecturers for Atmospheric Water Resources Management Symposium - Continued

Date/Session	Topic	Lecturer
February 12 (cont.)		
p.m.-1	Seedability of cold clouds: opportunities	Dr. Vali
p.m.-2	Seedability of cold clouds: criteria and execution	Dr. Vali
February 13		
a.m.-1	Seedability of warm clouds: opportunities	Dr. Vali
a.m.-2	Seedability of warm clouds: criteria	Dr. Vali
p.m.-1	Review of past experiments: Caribbean warm clouds	Dr. Vali
p.m.-2	Review of past experiments: Florida and India warm clouds	Dr. Vali
February 15		
a.m.-1	Review of past experiments: Israel cold clouds	Dr. Vali
a.m.-2	Review of past experiments: HIPLEX cold clouds	Dr. Vali
p.m.-1	Seeding agents for warm clouds	Dr. Vali
p.m.-2	Seeding techniques for warm clouds	Dr. Vali
February 16		
a.m.-1	Seeding with artificial nuclei	Dr. Vali
a.m.-2	Seeding techniques for ice nuclei	Dr. Vali
p.m.-1	Optimum seeding rates	Dr. Vali
p.m.-2	Transport and dispersion of seeding material	Dr. Vali
February 17		
a.m.-1	Observational techniques: aircraft position and air motion	Dr. Vali
a.m.-2	Observational techniques: aircraft: state parameters	Dr. Vali
p.m.-1	Observational techniques: aircraft: liquid water content	Dr. Vali
p.m.-2	Observational techniques: aircraft: hydrometeors	Dr. Vali
February 18		
a.m.-1	Observational techniques: radar: principles	Dr. Vali
a.m.-2	Observational techniques: radar: parameters	Dr. Vali

Table 2.4. - Topics covered and lecturers for Atmospheric Water Resources Management Symposium - Continued

Date/Session	Topic	Lecturer
February 18 (cont.)		
p.m.-1	Observational techniques: radar: operation	Dr. Vali
p.m.-2	Observational techniques: radar: applications	Dr. Vali
February 19		
a.m.-1	Observational techniques: radiometer	Dr. Vali
a.m.-2	Observational techniques: surface networks	Dr. Vali
p.m.-1	Observational techniques: satellite data	Dr. Vali
p.m.-2	Observational techniques: others	Dr. Vali
February 22		
a.m.-1	Introduction to computer models of clouds	Dr. Orville
a.m.-2	Conservation equations	Dr. Orville
p.m.-1	Conservation of energy	Dr. Orville
p.m.-2	Meteorological thermodynamics	Dr. Orville
February 23		
a.m.-1	Meteorological thermodynamics (cont.)	Dr. Orville
a.m.-2	Microphysical concepts	Dr. Orville
p.m.-1	Microphysical concepts (cont.)	Dr. Orville
p.m.-2	One-dimensional, steady-state models	Dr. Orville
February 24		
a.m.-1	Results with one-dimensional, steady-state models	Dr. Rasmussen
a.m.-2	One-dimensional, time-dependent models	Dr. Orville
p.m.-1	Results with one-dimensional, time-dependent models	Dr. Rasmussen
p.m.-2	Two-dimensional, time-dependent models	Dr. Orville
February 25		
a.m.-1	Applications of two-dimensional, time dependent models	Dr. Orville
a.m.-2	Applications of two-dimensional, time-dependent models (cont.)	Dr. Orville
p.m.-1	Three-dimensional, time-dependent models	Dr. Orville
p.m.-2	Mesoscale effects in three-dimensional models	Dr. Rasmussen

Table 2.4. - Topics covered and lecturers for Atmospheric Water Resources Management Symposium - Continued

Date/Session	Topic	Lecturer
February 26		
a.m.-1	Results with three-dimensional,time-dependent cloud models	Dr. Rasmussen
a.m.-2	Warm cloud analogues of Thailand clouds; comparisons with observations	Dr. Orville
p.m.-1	Continuation of a.m.-2	Drs. Orville/Rasmussen
p.m.-2	Summary session on models	Drs. Rasmussen/Orville
February 29		
a.m.-1	Introduction to statistical design and evaluation of rainmaking operations	Mr. Medina
a.m.-2	Basic statistical concepts	Mr. Medina
p.m.-1	Basic statistical concepts (cont.)	Mr. Medina
p.m.-2	Least absolute deviation regression	Mr. Medina
March 1		
a.m.-1	Motivation for MRPP (multiresponse permutation procedure)	Mr. Medina
a.m.-2	MRPP technique	Mr. Medina
p.m.-1	Rerandomization; use in weather modification	Mr. Medina
p.m.-2	Experimental design; randomization methods; physical evaluations	Mr. Medina
March 2		
a.m.-1	Conceptual models for rainfall augmentation	Mr. Medina
a.m.-2	Design of a project; response variables	Mr. Medina
p.m.-1	Design alternatives; sample size estimation	Mr. Medina
p.m.-2	Design of a project for Thailand	Mr. Medina
March 3		
a.m.-1	Nowcasting/forecasting I	Mr. Reynolds
a.m.-2	Nowcasting/forecasting II	Mr. Reynolds
p.m.-1	Nowcasting/forecasting III	Mr. Reynolds
p.m.-2	Directing seeding operations	Mr. Reynolds
March 4		
a.m.-1	Seeding operations	Mr. Reynolds
a.m.-2	Data management	Mr. Medina
p.m.-1	Data collection; estimation of effects	Mr. Medina
p.m.-2	Estimation of treatment effects	Mr. Medina

Table 2.4. - Topics covered and lecturers for Atmospheric Water Resources Management Symposium - Continued

Date/Session	Topic	Lecturer
March 7		
a.m.-1	Socioeconomic considerations I	Dr. Silverman
a.m.-2	Socioeconomic considerations II	Dr. Silverman
p.m.-1	Benefit-cost analysis I	Dr. Silverman
p.m.-2	Benefit-cost analysis II	Dr. Silverman
March 8		
a.m.-1	Thailand drought warning study plans I	Dr. Thanawat
a.m.-2	Thailand drought warning study plans II	Dr. Thanawat
p.m.-1	Environmental considerations I	Mr. Reynolds
p.m.-2	Environmental considerations II	Mr. Reynolds
March 9		
a.m.-1	Suspension criteria	Mr. Reynolds
a.m.-2	Extra-area effects	Mr. Reynolds
p.m.-1	Scientific planning I	Mr. Reynolds
p.m.-2	Scientific planning II	Mr. Reynolds
March 10		
a.m.-1	Scientific planning III	Mr. Reynolds
a.m.-2	Management considerations I	Dr. Silverman
p.m.-1	Management considerations II	Dr. Silverman
p.m.-2	Management considerations III	Dr. Silverman
March 11		
a.m.-1	RRRDI 5-year plan	Mr. Sommai
a.m.-2	RRRDI 5-year plan	Mr. Sommai
p.m.	Chairman of the closing ceremony	Mr. Sommai Surakul Deputy Permanent Secretary, MOAC
	Remarks of thanks	Mr. David Delgado USAID
		Dr. Bernard A.Silverman Bureau of Reclamation
		Mr. Metha Rajatapiti Director, RRRDI

Table 2.4. - Topics covered and lecturers for Atmospheric Water Resources Management Symposium - Continued

Date/Session	Topic	Lecturer
March 11 (cont)		
p.m.	Report by Chairman of the Technical Working Group for the 5-week core training	Mrs. Subongkot Jamikorn
	Closing remarks by the Chairman	Mr. Sommai Surakul

2.2 Assessment

The following assessment of the symposium is based upon the impressions of the lecturers, the results of tests given by some lecturers, and questionnaires completed by the participants. The questionnaires covered the facilities, the course content, the success of the lecturers in transmitting information, and the perceived usefulness of the information to the participants' future involvement in RRRDI programs.

The answers to the questionnaires indicated that nearly all participants considered the symposium useful and the material presented highly relevant to the RRRDI program. Some considered the material relevant to their individual activities. The topics ranked highest in terms of their usefulness to participants on an individual basis were general scientific background and environmental considerations.

Except for 2 days, February 24 and 25, when lectures were presented at the Chiang Mai Land Development Center, all lectures were given at the Orchid Hotel in Chiang Mai, where the lecturers and some of the participants were housed. A classroom was set up at the hotel. With assistance from the Technical Working Group for the 5-Week Core Training and from the USAID mission in Bangkok, the classroom was provided with projectors for slides and transparencies, players for video cassettes, and personal computers. In completing their questionnaires the participants gave high marks to the physical arrangements, particularly to the lighting and to the sound system.

The fact that the course was given at the hotel where the lecturers stayed meant that the lecturers were available for discussions with the seminar participants for some time each day outside of the classroom. This more personalized instruction was particularly valuable in helping the participants with work on the personal computers, including cloud model runs. Two lecturers were present on some days due to the intentional overlapping of their stays at Chiang Mai; this further increased their accessibility for instruction outside of the formal classroom setting. Evening work with the personal computers was a common occurrence.

The facilitators were very effective and their presence was highly beneficial. All participants ranked the services of the facilitators in the highest two out of four possible categories on their questionnaires. The special lecture on cloud modeling given in Thai by Dr. Patipat on February 27 was also very beneficial to the participants. However, progress in future training would be enhanced greatly if all participants were thoroughly proficient in English so they could communicate more effectively with their U.S. counterparts.

Each lecturer prepared extensive notes on the material he presented. These notes, along with copies of the opening and closing addresses and the detailed results of the questionnaires, have been published in a hard-bound volume of symposium proceedings. The proceedings and lecture notes will be valuable training aids for all Thai personnel who become involved in the project in the future.

3. EVALUATION OF SCIENTIFIC CONCEPTS

3.1 Introduction

Two basic scientific concepts have been advanced for increasing precipitation by cloud seeding: (a) seeding can increase the precipitation efficiency of clouds - that is, seeding can increase the amount of rain or snow falling from clouds without changing the total amount of water vapor condensed to form those clouds, and (b) seeding can modify cloud dynamics leading, for example, to a larger or more persistent cumulus cloud that yields more rainfall.

Cloud treatment to increase the precipitation efficiency of clouds, which is sometimes called static seeding, is seeding for microphysical effects only. Attempts to put the concept into practice have involved two different approaches, with the choice depending largely upon the temperature structure of the cloud being treated. The first approach involves seeding clouds with tops extending above the 0 °C level with silver iodide or other ice-forming substances to promote the growth of artificial ice crystals. This approach is used currently in several countries to increase snowfall in mountainous areas and to increase rainfall from convective clouds. Static seeding is most attractive in clouds containing significant concentrations of supercooled water, which can support the growth of additional ice particles. The presence of persistent supercooled water can be interpreted as an indication that the concentration of natural ice nuclei is less than optimum for production of precipitation in that particular cloud system.

Seeding for microphysical effects in clouds that do not extend to the 0 °C level usually involves treatments with hygroscopic solutions or powders to speed the formation of rain by coalescence of liquid droplets. It is assumed that each hygroscopic particle or solution droplet grows rapidly by condensation until the resultant droplet becomes large enough to have an appreciable fall speed. When this occurs, the resultant hydrometeor grows by collection of smaller cloud droplets as well as by condensation and eventually falls out of the cloud as a raindrop. It has also been postulated that, under certain conditions, the falling raindrops multiply through a chain reaction process of drop breakup and subsequent growth of the resulting fragments by condensation and accretion into new raindrops. The assumption is that the efficiency of the precipitation process is increased by the addition of these artificial raindrop embryos to supplement the natural ones formed by chance collisions among the cloud droplets. This type of treatment can also be applied to clouds containing liquid droplets above the 0 °C level although, as noted above, such clouds are often treated with ice-forming agents instead because precipitation particles develop faster through ice growth processes. Hygroscopic seeding has been tested in several countries although not as widely as seeding with silver iodide. Apparent success in stimulation of rainfall by this method has been reported in India, Thailand, and Malaysia and in a few cases in the United States.

Seeding to produce dynamic effects is often directed at individual cumulus clouds, typically to increase their size and lifetime and thereby increase their total rainfall yield. In many cases dynamic effects have been sought by introducing silver iodide or other ice-forming agents into supercooled clouds to promote rapid freezing of supercooled water. The premise is that the artificially induced rapid cloud glaciation releases additional latent heat, thereby increasing cloud buoyancy and enhancing the updraft. Strengthening the updraft sometimes enables a cloud to grow taller and wider and to process more water vapor, thereby increasing precipitation. Clouds that respond to seeding by changes in size, cloud lifetime, or updraft speeds are said to possess dynamic seedability. Some scientists have defined dynamic seedability as the increase in cloud height predicted to result from seeding. However, seeding may have other dynamic effects; for example, the intensification of downdrafts induced by rain shafts.

The choice of seeding techniques for Thailand obviously depends upon the characteristics of the clouds to be treated. Important rains for agricultural production in Thailand fall mostly from April through October and the RRRDI program is in operation for most of that period each year. The prevailing air masses during the rainy season are hot and humid; and cloud bases are very warm, generally near 20 °C. Rain initiation is principally through the coalescence of liquid droplets. Precipitation processes involving interactions between ice particles and supercooled cloud droplets occur only in the upper parts of the larger clouds.

The RRRDI program in Thailand has been designed principally to increase rainfall from warm cumulus clouds. The RRRDI uses an aircraft seeding technique designed to modify the weather in three steps. The first step is to upset the stability of the atmosphere by releasing exothermic chemicals near the CCL (convective condensation level) and/or endothermic chemicals 1 or 2 kilometers above the CCL. The second step is to stimulate cloud development by releasing endothermic and hygroscopic chemicals 1 kilometer or so above the cloud base level in or around or immediately upwind of existing clouds. The final step is to enhance the rainfall in a variety of ways, including dropping dry ice or releasing endothermic chemicals into clouds around 3 to 4 kilometers above sea level and releasing hygroscopic and endothermic chemicals near cloud base (Silverman et al., 1986).

Under the current PASA, Reclamation has carried out an evaluation of the scientific concepts considered potentially applicable to clouds in Thailand. This evaluation was accomplished by running numerical cloud models on computers. Cloud models were introduced into weather modification experiments in the 1960's and have proven useful in their design, conduct, and evaluation. The remainder of this chapter gives a brief description of the types of cloud models used for the study, summarizes the results of the model runs performed, compares the results to those of numerical modeling experiments performed elsewhere, and relates the results to observations of actual clouds in Thailand and elsewhere. A more detailed discussion of the models used and results of individual modeling runs are given in appendix A.

3.2 Selection of Appropriate Cloud Models

The numerical models available for simulating the effects of cloud seeding range from very simple ones to investigate the growth of a single cloud droplet by condensation to complex cloud models capable of simulating the effects of artificial heat releases on the dynamics of a cumulus cloud. Cloud models can be classified as one, two, or three dimensional in space. In one-dimensional models the dimension represented is normally height. One also distinguishes between steady-state and time-dependent models, and between kinematic and dynamic models. Wind fields, including updrafts and downdrafts, are assumed in kinematic models; dynamic models try to predict wind fields from the initial and boundary conditions imposed. The conditions imposed normally include one or more atmospheric soundings to specify the air mass in which the cumulus cloud forms. Increasing the number of dimensions involved, going from steady state to time dependence, and going from kinematic to dynamic models all increase markedly the amount of computer resources required to make one run of a cloud model. However, the computer power required is impacted even more by decisions regarding the handling of the microphysical processes within a cloud model. Models which attempt to distinguish among various types of solid and liquid hydrometeors and to keep track of their evolving size distributions require very powerful computers.

For the present study, it was considered necessary to model the interactions between the large-scale atmospheric motions and the topography of Thailand, the interactions between the mesoscale motions (scale of about 25 to 250 km) and developing cumulus clouds, and the microphysical processes within individual cumulus clouds. Large-scale models capable of simulating the response of wind currents to underlying terrain have proven valuable in explaining rainfall patterns in Hawaii and California and were expected to be useful for explaining rainfall patterns in Thailand also. For that purpose, we chose the Clark (1977) three-dimensional model. This is a very sophisticated model making use of the nested grid technique (see appendix A). The Clark three-dimensional model runs were made on the CRAY-X1 computer at the NCAR (National Center for Atmospheric Research) in Boulder, Colorado. Because of the high cost of running the model and the large amounts of time required to interpret its results, only two cases were performed in this study. Results are discussed in section 3.3.

In order to examine a few more cases within the design development time frame, some runs were made with a two-dimensional version of the Clark model. This version makes simplifying assumptions about the vertical structure of the atmosphere. It does not provide the universality of the Clark three-dimensional model, but can be used to extend the range of predictions based on a few three-dimensional model runs, especially in situations where the wind direction does not vary much with height and the air flows over rather than around any mountains present. Both of these conditions hold for most of the summer monsoon period in the area of interest in Thailand, giving some confidence in the two-dimensional model results. The two-dimensional runs are also discussed in section 3.3.

In order to analyze a large number of soundings, the MESOCU model was chosen, which is a steady-state, one-dimensional model with bulk microphysics. The main advantage of MESOCU is that it executes quickly on a computer of moderate power. However, because of all the simplifications made, this model does not reliably predict details of cloud evolution. MESOCU has been used in the present study to estimate cloud top temperatures that are likely to be observed for a given air mass and to predict the potential for cloud growth due to glaciogenic seeding.
The studies of responses to seeding by individual clouds required a model capable of simulating both the microphysical and dynamic responses of cumulus clouds to seeding with both hygroscopic and glaciogenic (ice-forming) agents. Therefore, there was a requirement for a time-dependent model with fairly sophisticated microphysics. In order to hold computer requirements down to a reasonable level and permit making a significant number of model runs within the time constraints of the PASA, the decision was made to use a one-dimensional model. Obviously, this choice precludes any study of wind shear effects or of recirculation of falling raindrops back into an updraft. The particular model chosen was based on previous model development by Silverman and Glass (1973), which was extended by Nelson (1979), and further refined by Rasmussen et al. (1989). This model is hereinafter referred to as the Nelson model. Details of the Nelson model are given in appendix A.

3.3 Results of Model Runs

The three-dimensional runs with typical soundings for Port Blair, India, the upwind radiosonde station in the Andaman Islands, show upward air motion on the windward side of most ridges. It is apparent that orographic lifting by the mountains along the Burma-Thailand border strongly influences rainfall patterns in western and northwestern Thailand. The model predicts downdrafts on the lee side of most mountains, leading to diminished rainfall eastward from most ridges. These results are in general agreement with observations. The supplementary two-dimensional model runs generally confirm the predictions of the three-dimensional model runs. These runs also show the importance of wind shear in cloud development. For cases where the wind reverses direction with height at a low elevation, cloud development is suppressed. The reversal of the wind between the ground and upper levels also favors the production of anvils from cold clouds. Most of the two-dimensional model runs did not show significant effects due to glaciogenic seeding, even when a weak inversion was present. However, a case with the wind reversal level at low altitude showed a 30-percent increase in precipitation over the simulated natural case. Apparently, the seeding provided enough additional buoyancy to induce increased vertical development of clouds that otherwise were dissipating due to the effects of wind shear at low levels. Because of the presence of significant moisture at all levels in the soundings, the seeded clouds still had sufficient low-level moisture to continue growing.

The MESOCU model runs predicted clouds with top temperatures between -10 and -20 °C for many of the soundings used. Previous studies in other regions have indicated that such clouds often have a good potential for increased growth by glaciogenic seeding. The MESOCU model runs to simulate glaciogenic seeding confirmed this previously noted tendency. About 35 percent of the runs made indicated an increase in cloud top height of 1 kilometer or more would be produced by glaciogenic seeding. Results of this study were about the same for both the Chiang Mai and Port Blair soundings.

Runs with the one-dimensional Nelson model were made principally to test the effects of hygroscopic seeding and of seeding with silver iodide for dynamic effects. The results indicate that hygroscopic seeding speeds the formation of rain, typically by about 8 minutes. Such a speeding of the rain process could well lead to light showers from clouds that would otherwise not produce rain before dissipating. The model results also suggest that total rainfall from the small clouds that ordinarily produce light showers would be increased. The Nelson model runs, like those with MESOCU, indicate that dynamic seedability is present in the cold clouds on some days. This is an interesting result, as it suggests that on those days the potential exists for substantial increases in rainfall through increases in the size and duration of cumulus clouds.

There are a few situations of special interest. One of these includes days when clouds form which are capped by stable layers, so that they do not grow very tall. The models suggest that, on some of these days, glaciogenic seeding could lead to penetration of the stable layers and substantial additional cloud growth.

3.4 Implications for the RRRDI Program

The modeling studies, along with a survey of available data on cloud types likely to be present in Thailand, suggest classifying the cumulus clouds into three categories as follows: (a) cumulus clouds that do not grow tall enough to develop ice (warm cloud), (b) cumulus congestus that grow tall enough to develop ice but do not have dynamic seedability, and (c) cumulus congestus that grow tall enough to develop ice and that possess dynamic seedability. The existence of cloud treatment potential for beneficial effects on these clouds is based on results from one-, two-, and three-dimensional cloud model runs and on results from some previous field experiments conducted elsewhere.

3.4.1 Seeding for Microphysical Effects. - Seeding to increase the precipitation efficiency of a cloud through microphysical effects (static seeding) has been discussed above. The successful use of static seeding requires ample knowledge of the precipitation mechanisms of the clouds to be treated. Therefore, some additional information on precipitation processes is presented here before the conclusions.

Research has indicated that graupel plays an important role in the formation of precipitation in cumulus congestus clouds (Mason, 1971; Braham, 1981). It is believed that graupel develops from ice crystals that grow initially by vapor deposition and then by riming (referred to as the IRG mechanism by Silverman, 1986), or, in some clouds, from drizzle drops which form by coalescence, freeze, and then continue to grow by riming (referred to as the CRG mechanism by Silverman). It appears that one or the other mechanism is usually dominant in each cloud, which has implications for the use of static seeding. In his review on static seeding, Silverman (1986) states, ". . . no cause-and-effect argument has been presented which details how the efficiency of the CRG mechanism can be improved by glaciogenic seeding." The CRG process appears to occur most frequently in clouds with base temperatures exceeding 10 °C. Cloud base temperatures over the Bhumipol Dam region during the May-October period are near 20 °C, suggesting that the CRG mechanism occurs there frequently.

One possible reason why clouds in which the CRG mechanism is operative do not appear favorable for static seeding with glaciogenic agents is that the same mechanism may lead to secondary ice crystal production. Mossop (1985) found that favorable conditions for secondary ice crystal production include the presence of supercooled droplets of at least 24 micrometers in diameter at temperatures of about -10 °C and warmer. Mixed-phase clouds over the proposed study area with their warm bases and maritime drop-size distributions (large droplets in low concentrations of 30 to 100 cm^{-3}) are likely to experience secondary ice crystal production, which means that precipitation efficiency would not be affected by a scarcity of ice crystals.

The material just presented argues that seeding Thailand clouds for microphysical effects should be done with hygroscopic agents rather than ice-forming agents, even in those cases where the cloud tops eventually rise above the 0 °C level. Timely cloud treatment near cloud top is expected to lead to the production of additional large droplets and, consequently, initiation and/or enhancement of the coalescence process so that the rainfall probability and the amount of precipitation would be increased.

Microphysical changes are expected to be the primary result of hygroscopic seeding as cloud model runs have not indicated dynamic effects occurring in the limited number of cases examined thus far. A more detailed statement of the physical hypothesis which describes the expected sequence of events for warm clouds treated with hygroscopic agents is given in section 4.

3.4.2 Seeding Mixed-Phase Clouds for Dynamic Effects. - Clouds rising above the 0 °C level are generally large enough and long-lasting enough to precipitate naturally. As noted above, it is expected that these clouds will develop enough natural ice, possibly through secondary ice crystal production, for an efficient precipitation process. Therefore, seeding these clouds for microphysical effects only is not expected to be productive. On the other hand, there are indications that seeding them for dynamic effects could be productive. As noted above, the model runs suggest that dynamic seedability is present in cumulus clouds on perhaps 35 percent of the operational days on the RRRDI program. As long as SLW (supercooled liquid water) is present, the presence of ice crystals does not preclude the production of dynamic effects by seeding with ice-forming agents. All that is required is that some SLW remain that can be converted artificially to ice, thereby releasing latent heat. The Thailand clouds with their anticipated high concentrations of SLW, much of it in the form of large droplets, should be ideal candidates for seeding for dynamic effects. A detailed physical hypothesis for the effects of such seeding is given in section 4.

4. DESIGN OF THE DEMONSTRATION PROJECT

4.1 Target Area

One objective of the scientific concept evaluations described in section 3 and of certain statistical studies to be described below has been to arrive at a design for a cloud seeding demonstration project for Thailand. The design presented also takes into account information on the weather systems affecting Thailand at different times of the year and availability of necessary facilities including airports, roads, and communication systems around proposed field sites. Some of the information used for project design was collected during visits to Thailand by Reclamation personnel early in 1988. In searching for a location for the demonstration project, Reclamation personnel looked for sites that are reasonably accessible, provide weather situations fairly typical of Thailand, and do not have highly complex topography, which would make interpretation of results unduly difficult. With the cooperation of officials of the Royal Thai Government, Reclamation and RRRDI personnel were able to visit potential experimental sites and appraise their suitability. The Royal Thai Government officials also provided information on the types of radar sets, aircraft, and other essential equipment already available for the project.

The experimental site survey identified two areas that are potentially suitable for the demonstration project - one in the northern part of the Bhumipol catchment area west-southwest of Chiang Mai and one in the southern part of the catchment area west-northwest of the Bhumipol Dam. The southern site was selected because the terrain is more suitable and offers a considerably better site for the project radar. In addition, the Electricity Generating Authority of Thailand recommended the southern site because rain falling in that area flows into the Bhumipol Reservoir. They noted that some of the rain from the northern site would not reach the Bhumipol Reservoir as it would likely be diverted by the many small dams and reservoirs that have been constructed recently in the north. Therefore, it is recommended that the demonstration project be carried out over the ridge oriented approximately north-south, located just west of the city of Omkoi in western Thailand (see fig. 4-1). The ridge briefly turns eastward just north of Omkoi then northward. Its highest point is near the southern end, near 17°11'N., 98°29'W., and is about 1800 meters above sea level. The east side of the ridge drains into the Nam Mae Tun River, which is one of the streams feeding into Bhumipol Reservoir.

As figure 4-1 shows, the target ridge is near the Burmese-Thai border, which in that area follows the Thaungyin River. Upwind of the target ridge, there is only one important barrier, the Dauna Range in Burma about 35 kilometers to the southwest. The Dauna Range is about the same height as the target ridge and has the same northwest-southeast orientation but is not as wide. The shore of the Bay of Bengal is located about 150 kilometers to the southwest of the target ridge. Consequently, the suggested target area is well exposed to maritime air masses flowing into Thailand from the southwest.

4.2 Expected Seeding Opportunities

The area recommended for the demonstration project is expected to provide about 100 days with clouds suitable for experimentation in a typical operational season. Actual counts of the number of days with treatable clouds over the ridge are not available. However, cloud model results

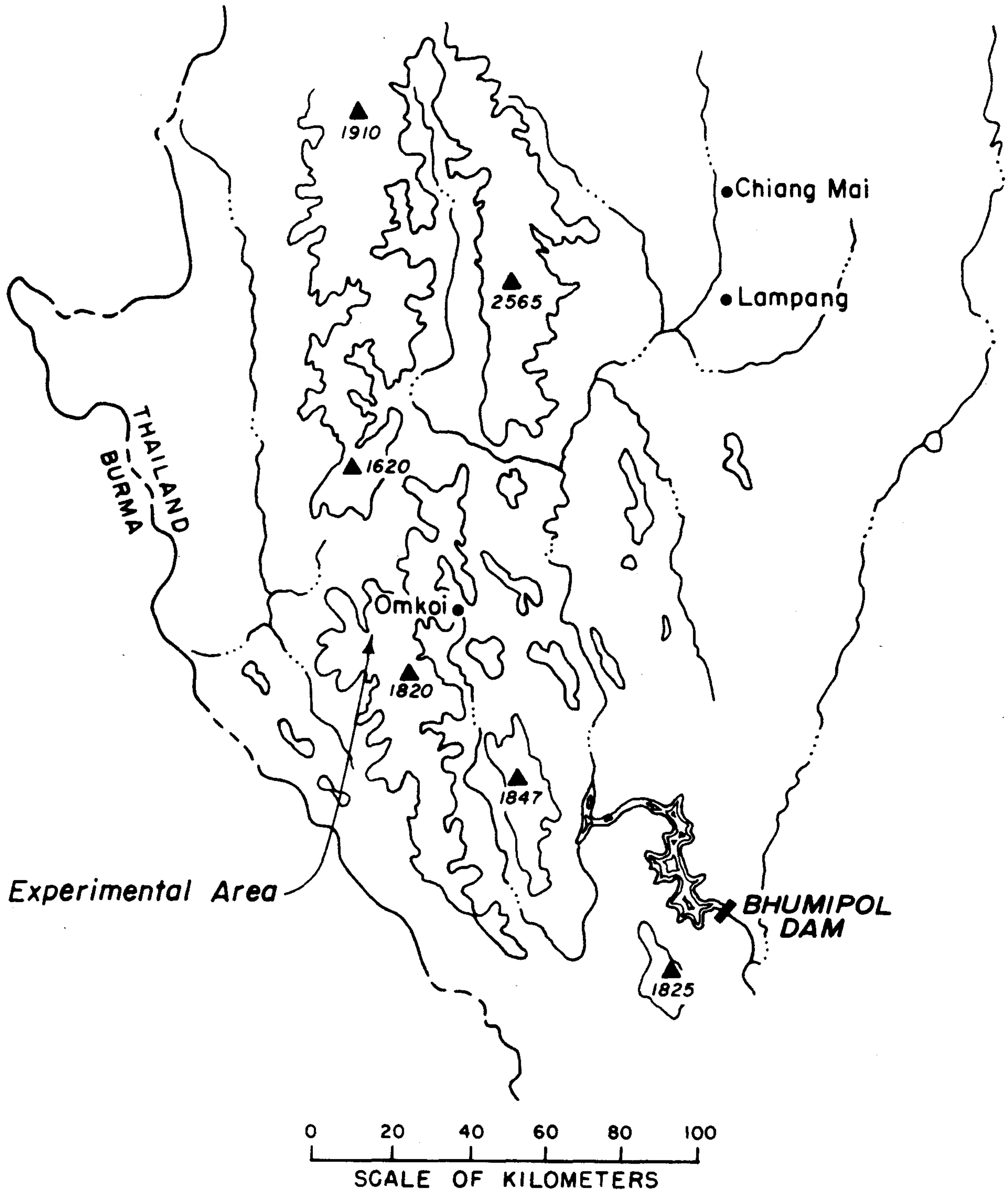

Figure 4-1. - Map showing location of experimental area for demonstration project.

(see appendix A) obtained with soundings from Port Blair in India's Andaman Islands and from Chiang Mai suggest that clouds with treatment potential will exist at some time during most days with precipitation. Values given in table 4.1 indicate that at Omkoi, located on the lee of the target ridge, the mean number of days per season with measurable precipitation is about 90 with extreme values of 48 to 124 days per season. The precipitation frequencies for Omkoi are likely underestimates of the frequencies at higher elevations on the ridge to the west. Therefore, an estimate of 100 days per season presenting opportunities for experimental seeding over the target ridge appears reasonable.

Table 4.1. - Number of days per month with measurable precipitation at Omkoi, Thailand

Year	May	June	July	Aug.	Sept.	Oct.	Total
1952	13	23	17	23	21	27	124
1958	7	10	11	12	11	7	58
1959	18	10	13	15	22	6	84
1961	7	5	13	21	27	16	89
1962	4	8	11	16	11	12	62
1964	9	6	6	13	19	16	69
1965	10	11	7	8	7	5	48
1966	14	16	13	11	16	6	66
1968	14	22	21	21	18	15	111
1969	20	18	18	24	12	16	108
1970	15	10	13	24	21	17	100
1971	21	16	18	25	16	12	108
1972	17	16	12	11	11	5	72
1973	11	12	12	16	18	13	82
1974	17	14	12	17	12	8	80
1975	23	19	21	20	21	11	115
1976	11	14	21	28	20	19	113
1977	16	8	18	16	17	20	95
1978	14	18	13	17	22	12	96
1979	10	17	17	20	21	7	92
1980	16	19	16	14	26	19	110
1981	15	23	17	17	16	13	101
1982	19	20	15	18	22	12	106
1983	5	13	6	20	20	14	78
1984	11	18	12	14	22	14	91
1985	18	23	10	13	16	14	94
Average	14	15	14	18	18	13	90.5

Table 4.2 gives precipitation totals for Omkoi for the months covered in table 4.1. The average seasonal precipitation is 782 millimeters. September is the wettest month with a mean of 198 millimeters and June and July are the least wet months of the rainy season, with about 94 millimeters of rainfall each. Monthly extremes are 7.5 and 420.4 millimeters. The crossing northward and later southward of the intertropical convergence zone is clearly evident in the monthly means as May and September are noticeably the wettest months.

Table 4.2. - Monthly precipitation observed at Omkoi, Thailand (in millimeters)

Year	May	June	July	Aug.	Sept.	Oct.	Total
1952	22.7	52.3	48.0	23.6	21.7	50.9	219.2
1958	13.3	18.6	27.8	28.7	76.6	15.2	180.2
1959	78.0	12.9	31.7	42.0	403.3	109.0	676.9
1961	15.1	7.5	18.6	20.3	21.2	20.5	103.2
1962	28.6	65.3	130.5	204.2	287.7	200.3	916.6
1964	194.9	140.0	131.5	93.6	266.2	222.3	1048.5
1965	161.9	139.1	70.4	150.9	190.5	45.4	758.2
1966	355.8	19.9	100.9	98.3	163.5	59.2	797.6
1968	170.8	85.2	149.8	88.0	99.0	81.2	674.0
1969	385.9	96.2	228.7	234.1	151.8	91.9	1188.6
1970	121.0	34.2	33.0	242.1	192.6	98.1	721.0
1971	130.5	58.1	52.4	155.9	98.4	42.0	537.3
1972	91.3	70.1	16.4	14.4	87.6	30.2	310.0
1973	30.7	30.5	61.3	85.6	316.9	103.5	628.5
1974	189.1	66.8	45.5	194.8	179.9	59.9	736.0
1975	420.4	296.4	249.0	137.7	160.7	50.5	1314.7
1976	34.3	83.0	101.7	193.5	168.7	213.1	794.3
1977	165.0	50.8	77.6	132.2	194.0	187.9	807.5
1978	147.7	141.4	186.1	100.6	219.5	159.7	955.0
1979	184.1	183.5	105.7	130.8	201.3	82.2	887.6
1980	213.7	111.2	91.3	137.8	343.5	289.0	1186.5
1981	192.9	112.9	130.9	108.4	156.1	139.2	840.4
1982	267.6	116.2	121.4	103.5	297.8	117.3	1023.8
1983	71.4	69.6	38.4	139.8	177.7	108.8	605.7
1984	103.5	124.3	65.8	101.9	284.2	148.5	828.2
1985	156.6	169.7	38.1	99.6	195.2	163.8	823.0
Average	157.9	94.2	94.1	22.5	198.2	115.6	782.5

The rainfall amounts at Omkoi are likely an underestimate of amounts on the target ridge. Therefore, the runoff from the east side of the target ridge contributes significantly to the inflow to Bhumipol Reservoir and that increases in rainfall there would contribute valuable additional inflow to the reservoir.

The correlation coefficient between the number of rainy days per season, based on data in table 4.1, and the seasonal rainfall, based on data in table 4.2, has been calculated at 0.22, which shows that the relationship between the two quantities is weak. It is suspected that a few very wet days, rather than an increase in frequency of rainfall events, make the difference between wet and dry years. Therefore, it is not expected that the number of seeding opportunities will diminish significantly in dry years in proportion to the deficiency in rainfall. The numbers of rainy days shown in table 4.1 remain as the best guide to the number of seeding opportunities in both wet and dry years.

4.3 General Field Project Layout

For reasons discussed in section 4.4.2, it is recommended that a randomized crossover design be used for the demonstration project. This means that two target areas would be instrumented on the target ridge with a buffer zone between them that is never seeded. Declaration of an experimental unit requires that one of the target areas be selected at random for cloud seeding. The unseeded target area would serve as the control for that experimental unit. In order to avoid contamination, the two target areas should be separated from each other across the prevailing wind, rather than in an upwind-downwind configuration. This requirement can be met by locating one target area on the extreme northern part of the target ridge and the other further south, with a 15- to 20-kilometer buffer zone between them.

The target areas are about 30 kilometers long (north-south) and extend all the way across the target ridge (see fig. 4-1 for terrain layout). The plan is to identify suitable clouds on the upwind (usually southwest) side of the ridge and seed the clouds as they move into the target area. Observations of possible effects would be taken across the ridge and on the downwind side at least as far as the Nam Mae Tun River, which drains into the Bhumipol Reservoir. The next ridge downwind, which forms the eastern border of the valley, would not be considered part of the target area but would be monitored for downwind effects. The target areas should be considered as tentative. As the project materializes, adjustments may be made based on availability of sites for instrumentation or on results of preliminary cloud surveys and other site specific design studies. The exact layouts will be shown in the Demonstration Project Operations Plan.

In order to conduct operations over the proposed target areas, it will be necessary to provide the following ground facilities: a weather radar site, a dense rain gauge network with a servicing center, a field operations office complete with forecast center and briefing room, a radiosonde observation center, and a base for project aircraft. It has been convenient in some previous projects to colocate the weather radar, field operations office, and aircraft base. In the present case, colocation does not appear feasible as the available airports do not provide good radar coverage of the target areas. The radar will need to be installed at a location from which clouds over the target areas can be easily scanned.

It is recommended that the project aircraft be based at the airport at Bhumipol Dam and that the field project office be set up at the damsite or at its airport. The weather station at the field office should be equipped with a remote satellite recorder and a facsimile machine for receiving current weather maps, charts, and weather reports. In cases where flights in or out of the airport at Bhumipol Dam are precluded by bad weather, the airports at Tak and Chiang Mai could serve as alternates. The radiosonde observation center should be located at Tha Song Yang so that data most representative of air flowing into the target area can be collected.

A ground-based weather radar is essential to conduct the operations. Furthermore, radar data will be central to the evaluation. The plan is to estimate rainfall in the target areas during experimental units on the basis of radar data calibrated by the network of recording rain gauges. The recommended radar site is about 9 kilometers east of Omkoi. It provides a good view of the target ridge and downwind areas. Recommendations concerning the radar set are provided in section 4.5. More information on specific aspects of the project design is given in the following subsections.

4.4 Statistical Design

4.4.1 Statistical Hypotheses. - The statistical approach to be followed in evaluating the demonstration project will be that of hypothesis testing, where success is affected by the extent of differences between samples. Hypothesis testing involves setting one or more null hypotheses (hypotheses of no effect) and then determining if the available evidence is sufficiently strong to justify rejection of any or all hypotheses. In this framework, rejection of a null hypothesis indicates the treated and nontreated samples are different and suggests a seeding effect.

The null hypotheses as currently envisioned for the Thailand demonstration project are listed below. Additions or revisions may occur after preliminary calibration data collection and analysis take place and more cloud model results become available.

4.4.1.1 Warm cloud hypotheses. - Four tentative null hypotheses for the experimental units with hygroscopic seeding are listed:

H_{01}: Hygroscopic seeding does not affect the probability that rain will fall somewhere in the target area in the first hour after experimental unit declaration.

H_{02}: Hygroscopic seeding does not alter the mean area covered by rainfall during the experimental unit.

H_{03}: Hygroscopic seeding does not alter the total rainfall volume per experimental unit.

H_{04}: Hygroscopic seeding does not alter the rainfall pattern at the ground.

The first hypothesis is set up to test the concept that hygroscopic seeding sometimes causes rain to fall from clouds that otherwise would not produce any rain. This hypothesis can be tested in a straightforward way by observing, for each experimental unit, whether or not the rain-gauge-adjusted radar data indicate rain anywhere in the target areas during the first hour. Limiting consideration to the first hour is intended to reduce the masking of results by the formation of natural showers, which is virtually a certainty if events over the entire experimental unit are combined. Even so, this result tests for initiation of rain only if no natural rain falls anywhere in the target during the first hour.

The second hypothesis tests for the production of additional showers in the presence of some natural ones or for seeding-induced increases in the areal extent or persistence of natural showers. Unfortunately, testing this hypothesis does not by itself distinguish among these possibilities. *Post hoc* analyses will be undertaken to probe whether the data are adequate for study of the individual factors.

The third hypothesis is the most crucial of all as it involves total rainfall on the ground during an experimental unit. Evaluating this hypothesis requires integration over space and time of the rainfall estimated on the basis of rain-gauge-adjusted radar observations. However, rejection of this null hypothesis, while a very practical result, would say little about the mechanisms through which the effect was produced.

The fourth hypothesis has been introduced to provide some insight into the mechanisms by which hygroscopic seeding may alter rainfall. Testing of this hypothesis will also help determine whether the precipitation, if changed by seeding, is being increased or merely redistributed. Alteration of the rainfall pattern indicates one to all of the following: (a) initial precipitation deposition is altered as, for example, initial rainfall occurs further upwind; (b) on average, precipitation extends further downwind, that is, further down the lee side of the target ridge and beyond; and (c) precipitation distribution within the fallout area is altered (e.g., the peak amounts occur further upwind). Statistical procedures can test for a pattern change that is the cumulative effect of these three features or for the individual features. Calibration seeding may suggest that the individual features be tested separately. Hypotheses may be altered for this purpose and statistics modified to carry out testing. The advantage of dealing with the cumulative effect is the greater possibility of detection. More cases are required to detect a smaller real effect such as may occur from one of the three components listed.

4.4.1.2 Cold cloud hypotheses. - The null hypotheses for the cold cloud test cases are:

H_{05}: Glaciogenic seeding of mixed-phase clouds does not alter the rainfall volume per experimental unit.

H_{06}: Glaciogenic seeding of mixed-phase clouds does not alter the precipitation pattern at the ground.

Analysis of the seeding cases does not include the first two hypotheses used in the hygroscopic seeding cases. Cold clouds seeded for dynamic effects rise above the -10 °C level and therefore are likely to have precipitation already forming in them at the time of seeding. The purpose of the recommended cold cloud seeding is to stimulate cloud dynamics, leading to processing of additional water vapor and the production of additional rainfall. Calculation of response variables for the two hypotheses for the cold cloud cases would proceed in the same way as for the testing of the two corresponding hypotheses for the hygroscopic cases.

4.4.2 Experimental Design, Experimental Units, and Treatment Units

4.4.2.1 Experimental design. - Selecting appropriate experimental units is crucial in designing a statistical experiment in weather modification. The material presented in section 3 has already identified cumulus clouds as the logical treatment units for the Thailand demonstration project. The statistical design would be simplified if the individual cumulus cloud could be identified as the experimental unit also. However, an experimental unit is defined here as the assemblage of all the clouds affecting the target area selected for treatment during a specified time period like 3 hours.

Experiments using individual cumulus clouds as experimental units have been conducted - for example, HIPLEX-1 in the United States. However, such experiments require very sophisticated navigation and meteorological instrumentation on the aircraft monitoring the test case clouds and the careful execution of precise flight procedures (Smith et al., 1984). Such experiments also leave unanswered important questions about possible interactions among neighboring clouds, so they cannot provide definitive answers to questions about the impact of seeding on rainfall over an area. It is for these reasons that the study of area rainfall, as opposed to rainfall from single clouds, is recommended.

Three experimental designs have been used widely in the past to evaluate possible effects of cloud seeding over an area: (a) single target, (b) target-control, and (c) randomized crossover designs (Dennis, 1980).

The single-target design involves a random sequence of either treating or not treating experimental units associated with a single specified target area. The analysis of results is based on differences between target area measurements for treated and nontreated experimental units.

The target-control design is more powerful than the single-target design. It, too, involves a random choice of either treating or not treating experimental units associated with a specified target area. However, measurements are also obtained from one or more control areas, which should be close enough to the target area to ensure that their measurements follow the same pattern of natural variability, yet far enough from the target area so that the treatment does not influence the measurements in them. Observations in the target area are adjusted on the basis of observations in the control area, thereby accounting for some of the natural variability. As a result, fewer cases are needed in comparison with the single-target design to detect a given level of treatment effect.

The randomized crossover design also adjusts for the natural variability among experimental units but in a way more efficient than that of the target-control design. The randomized crossover design involves two target areas which should be close enough to each other so that their measurements follow the same pattern of natural variability, and far enough apart so that the treatment of one will not affect the other. For example, if the two target areas are designated by X and Y, then the design calls for a random sequence of either treating X and not treating Y, or not treating X and treating Y. As a consequence, Y is a control area for X or vice versa, depending on whether X or Y is being treated. One of the target areas is treated for each experimental unit in contrast to the target-control design, where a predetermined proportion of the units is purposely left untreated.

The randomized crossover design for detecting changes in rainfall is recommended for the Thailand demonstration project because this design provides the greatest power to detect seeding effects and should be applicable to conditions there. This means that treatment effects can be detected with fewer experimental units and consequently a shorter field program.

4.4.2.2 Experimental units. - There remains the problem of fixing the time length of the experimental unit. The principal arguments in favor of short experimental units are that one obtains more experimental units that way and that the clouds treated within a unit are likely to be more homogeneous than those treated within longer experimental units. With more homogeneous clouds within each unit, stratification of experimental units in terms of meteorological conditions becomes more meaningful. Therefore, use of a day as the experimental unit is rejected in the present case because of the very strong diurnal variations in the clouds over Thailand in general and over the proposed target ridge in particular. The principal arguments against very short experimental units are the increased variability of rainfall over very short periods and the fact that measurement errors become increasingly important as the amount of rain to be measured becomes smaller. Indeed, for very short experimental units of less than an hour, the measurement errors can be larger than the effects to be detected. Consideration of these factors in the present case has led to a recommended 3-hour experimental unit. However, design calibration information should be collected and analyzed so that suggested revisions may be incorporated into the design.

Because of the possibility of residual effects of seeding agents on clouds over the target ridge, a 2-hour purge period will follow each experimental unit before another can be declared. Initial data collection and analysis will determine if the length of the proposed purge period requires adjustment.

4.4.2.3 Treatment units. - As indicated above, under the proposed design, each experimental unit can be viewed as an assemblage of all the clouds affecting the randomly selected target area during the 3-hour experimental unit. The treatment units are the individual clouds within each experimental unit. The experimental units will be divided at the time of their declaration into two categories depending upon the seeding treatment chosen. An experimental unit expected to be characterized by clouds rising above the -10 °C level will be classified as a dynamic seeding (cold cloud) unit. All other experimental units will be hygroscopic seeding (warm cloud) units. The determination of the proper category for a potential experimental unit will need to be made prior to unit declaration.

The classification of an experimental unit will not be changed once it has been declared. For example, once a hygroscopic seeding case is declared, the project director will not order dynamic seeding even if some clouds begin to tower above the -10 °C level. This restriction is necessary to maintain the integrity of the statistical analysis. However, there is no requirement that all experimental units on a given day belong to the same treatment category. For example, the forecast on a given day might be for shallow clouds under an inversion for a few hours in the morning, to be followed by towering cumulus with dynamic potential. In such a situation, it would be realistic to try to obtain two experimental units on the same day - a hygroscopic seeding experimental unit in the morning and a dynamic seeding experimental unit later in the day.

4.4.3 Stratifications. - As noted above, pretreatment stratifications of the experimental units in the Thailand program will be according to whether warm or cold clouds are to be treated (not both concurrently). Since field equipment will occasionally fail or require periodic maintenance, data archives for the individual experimental units will differ somewhat indicating a difference in data quality depending on the role of the missing information. Stratification of units by data quality will be required for the statistical evaluation. Important *a priori* specified stratifications by data quality are given below. Adjustments will be made once equipment is installed and operational problems and likely data quality are better known.

a. Volume rainfall estimated by use of only rain-gauge-adjusted radar estimated rainfall.

b. Volume rainfall estimated by a combined sample of rain-gauge-derived values and rain-gauge-adjusted radar estimates.

c. Volume rainfall estimated by rain-gauge-adjusted radar where more than 25 percent of rain gauge measurements in the target or control area are missing.

d. Volume rainfall estimated from rain gauge data only.

Once a randomization envelope is opened, the experimental unit becomes part of the *a priori* data set regardless of subsequent events. If the radar fails during the course of an experimental unit, cloud seeding will continue so long as vital information can be obtained. The rainfall will be estimated from the rain gauge network measurements plus those obtained by gauge-adjusted radar up to the point of failure. However, complete rainfall pattern information can only be obtained from gauge-adjusted radar rainfall. Strata will be necessary for analyzing results with and without experimental units where the radar failed during the operational period.

Following completion of an experimental unit, it may be classified according to other criteria for *post hoc* analytic purposes. Analysts on previous projects found it useful to stratify test cases on the basis of wind direction, wind speed, cloud top temperature, and dynamic seedability as determined from cloud models.

4.4.4 Bias. - Two types of errors occur in sampling a phenomenon - random and systematic. The latter, better known as bias, should be avoided in experiments to a practical extent; that is, there is little point in straining to reduce the level of systematic errors much below that induced by random errors. Efforts to reduce systematic errors in the Thailand project include the use of (a) block randomization, (b) a treatment notification procedure that lessens field crew opportunity to influence results, and (c) objective procedures for analysis of measurements obtained. The randomization procedure to be employed in Thailand produces a sequential list of experimental unit random decisions to treat or not treat a specific target area of two selected as part of the crossover design (if not treated, the second target would be treated). The procedure will be applied, separately, to warm and cold experimental units. The process involves two distinct types of randomizations. An unrestricted randomization is used initially to obtain a sequence of two distinct block sizes involving four and six experimental units (each size is sequentially selected with equal chance). If a block of size four is selected in the unrestricted sequence, then one block among all six distinct possibilities of four taken two at a time (for example, the two cases where the southern target area is treated) balanced (each area is treated the same number of times) blocks is selected with probability 1/6 (a restricted randomization among the six balanced blocks). Similarly, if a block of size six is selected, one block among all 20 distinct possibilities (statistical combinations) of six taken three at a time balanced blocks (each target is treated three times in the six cases) is selected with probability 1/20 (a restricted randomization among the 20 balanced blocks). If an experiment is terminated at any given time, then this randomization procedure forces the two types of treatments (southern area treated, northern area treated) to be applied approximately the same number of times.

The second important effort to avoid bias is the use of a fixed procedure in the notification to commence application of the treatment. The process entails the launching of cloud seeding aircraft to either target area. Upon an indication that an experimental unit may be declared, additional cloud seeding aircraft may be launched. Both areas must have seedable clouds verified in order to declare an experimental unit. When an experimental unit is declared, an envelope will be opened to obtain the random decision as to which area is to receive the treatment. This procedure along with block randomization will lessen bias that may be introduced by field personnel having prior knowledge of which area is to be treated.

The third effort at avoiding bias consists of objective handling of the rainfall data. Objective procedures for archiving and analyzing the rainfall data will be established before the project's first experimental unit is declared. Computer programs will be developed for error and consistency checking of collected data prior to the beginning of randomized cloud seeding. Efforts will be made to develop objective procedures for the processing of data obtained from aircraft and other field instrumentation.

4.4.5 Statistical Techniques for Analysis. - Upon collection, quality checking, and archiving of field data, the analysis process can begin. Statistical procedures for rainfall data processing should be developed, computer coded, and ready to be applied. The procedures will consist of the following:

a. Computation of volume rainfall for each target area for each experimental unit from rain gauge and radar data.

b. Estimation of gauge-adjusted rainfall for each point of a selected grid for each target area.

c. Estimation of the treatment effect on rainfall for each stratification.

d. Sorting of data according to preselected stratifications and preprocessing in preparation for application of a statistical test.

e. Development of P-values by application of MRPP (multiresponse permutation procedures) to each set of samples for each stratification (Mielke et al., 1982).

f. Interpretation of P-values according to *a priori* selected significance values.

g. Acceptance or rejection of established null hypotheses.

Estimation of the treatment effect on rainfall for each stratification shall be accomplished by computation of the ratio of the mean volume rainfall for the seeded sample to the comparable mean for the nonseeded sample. The computation process shall adjust for known climatic differences between the two areas.

For an description of the MRPP, the reader is referred to the Lecture Notes on Design, Implementation, and Evaluation of Rainmaking Operations (Medina, 1988) presented in Chiang Mai at the symposium described in section 2. The MRPP were selected because they do not require the assumption of the data behaving according to some distribution with specific parameters. Rarely will an investigator know the distribution of the response variable (like rainfall) and/or its alteration by the treatment. The MRPP depend only on the structure of the test statistic in question and the randomization of units to treatment assignments. Not requiring the assumption of some distribution by the response variable allows the selection of a test statistic that is based on logical and realistic ideas. The above procedures can be applied not only to volume rainfall but also to variables such as cloud dimensions and height of first radar echoes from newly developing showers, to test whether measurements in treated and nontreated units differed at some selected significance level (sample sizes must be large enough for meaningful results). The decision to test certain variables as part of the physical evaluation will be made upon obtaining preliminary field measurements during the calibration period.

Testing for changes in rainfall patterns in time and space requires that the sample items or objects be carefully defined. Differences attributable to cloud seeding can be investigated for specific pattern changes by examining rainfall in selected groups of grid points (points for which estimates of rainfall are developed, more densely distributed than the rain gauges themselves) such as the initial three western columns or the trailing five columns to the east. The combined effects of various shifts in space can be studied by consideration of all grid points. Rainfall shifts in time can also be examined by restricting time to intervals of interest. Because there may be a natural climate difference between the two targets, ranks will be employed in rainfall pattern analysis rather than actual measurements. Ranking separately within each target substantially decreases the influence of a climate difference. Statistical procedures will be reviewed and refined, if necessary, following inspection of calibration data.

4.4.6 Estimation of Sample Size. - The crossover design lends itself well to testing of differences between simulated samples with the statistical procedures described in the previous section. Simulations of potential experimental outcomes with relevant real data can be very informative in establishing program parameters such as estimates of the number of cases necessary to detect treatment effects (i.e., program duration). The available historical data used for this study were the daily rainfall amounts for Omkoi, which is located at the northern end of the Nam Mae Tun River valley. Although the gauge is located on the valley floor and the data consist of 24-hour totals, the variability of the rainfall values may be a useful estimate of that for 3-hour readings at higher elevations. In fact the variability of the single station record may easily exceed that for computed means for the project targets. Consequently, it was felt that useful estimates of sample size could be obtained from the Omkoi data set. Simulated treatment effects of 5, 10, 15, and 20 percent rainfall increases were employed in 100 simulations of cloud seeding program results with the Omkoi data, which consisted of 2,334 days drawn from 26 seasons. Sample size estimates were obtained for significance levels (α) of 0.05 and 0.10. Results are given on figure 4-2 for cases where the rainfall correlation between the two target areas is restricted to 0.82, 0.85, and 0.90. Additional results and a more thorough description of procedures employed including the data selection process that yielded samples with desired correlations are described in the Lecture Notes presented at the symposium (Medina, 1988).

As expected, results indicate substantial sensitivity to the correlation between the samples. With $\alpha = 0.05$ and a simulated increase of 10 percent, a sample of 30 cases yields a probability of detection of 81 percent when the correlation is 0.95, and 30 percent with a correlation of 0.82. The probability of detection is also known as the power of the test and is defined as the probability of correctly rejecting the null hypothesis in favor of the alternative hypothesis. Noticeable effect on the probability of detection is also observed when the simulated treatment effect is increased from 10 to 15 percent. Assuming a rainfall correlation of 0.90 between the two target areas, $\alpha = 0.05$, and a treatment effect of 10 percent, about 90 cases are required to achieve the 90-percent probability of detection. Assuming that the latter value is acceptable (an acceptable value will need to be established prior to randomized cloud seeding), these simulations indicate that (with a 90-

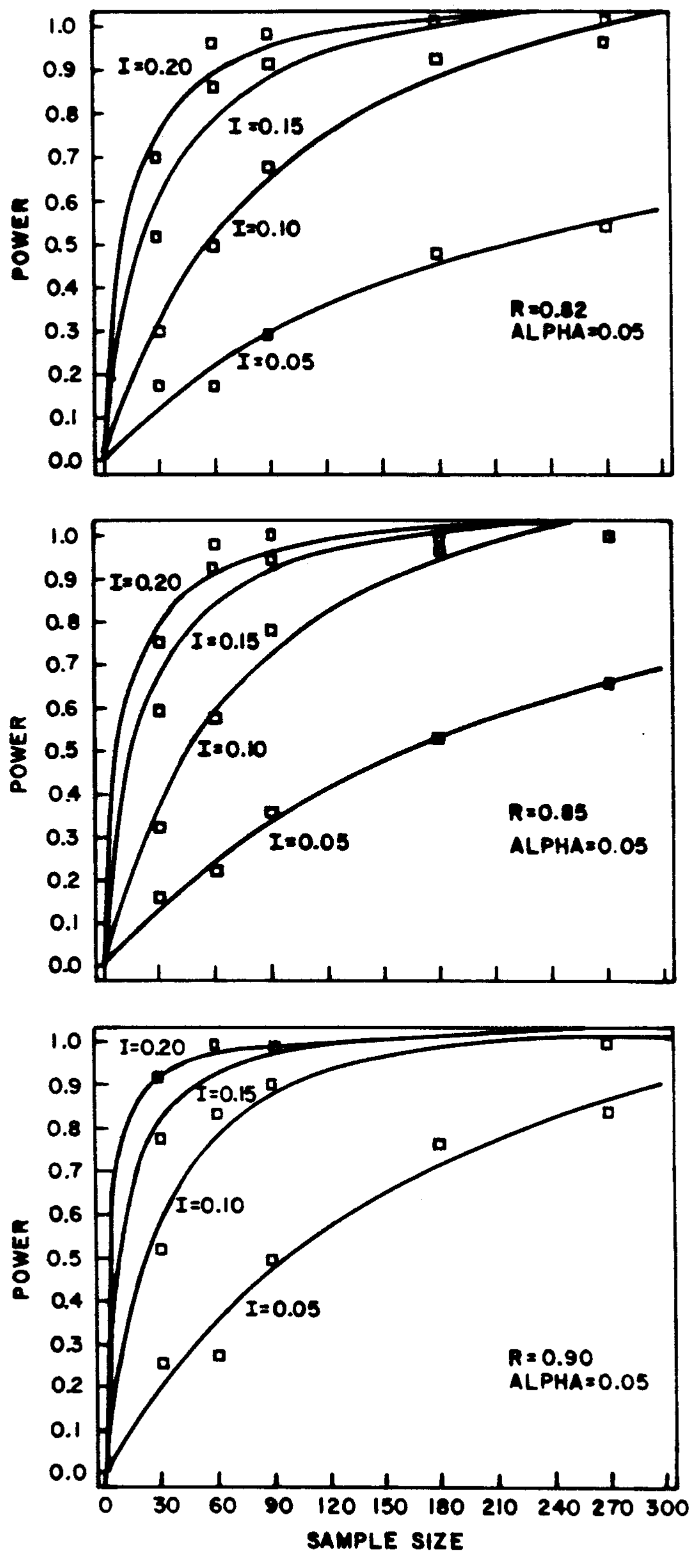

Figure 4-2. - Power versus sample size with treated-nontreated sample correlation R, α (significance level) = 0.05 and simulated increases of 5, 10, 15, and 20 percent.

percent probability of detection) 90 experimental units would be required per stratification to detect a 10-percent increase in rainfall at the 0.05 significance level. On the mean, Omkoi experiences rainfall on about 90 days per wet season (May-October). Under the assumptions that about 70 percent or approximately 60 days of the mean number of wet days offer treatable cases in both areas (experimental units) and the warm and cold units occur with equal frequency, randomized cloud seeding would need to be conducted for 3 years to sample the required number of cases. However, the warm/cold split is not likely to be even, equipment problems will prevent operations on some treatable days, and the climatic draw may be unfavorable. These factors suggest that at least 4 years of randomized cloud seeding will be required before any significant conclusions can be drawn.

4.5 Physical Hypotheses

4.5.1 Introduction. - As noted previously, the treatment units will be individual cumulus clouds. During experimental units without any synoptic scale or mesoscale forcing systems present, the clouds will be somewhat isolated from one another. During experimental units with such forcing systems present, the clouds will be more numerous and more vigorous and may tend to merge into lines or clusters.

Generally, cloud base is located at 1 to 1.5 kilometers above mean sea level, where the temperature is typically 20 to 25 °C. The freezing level is found at 5 to 5.5 kilometers. The -10 °C level is typically found at 6.5 to 7.0 kilometers, while the -25 °C level is at 9 to 9.5 kilometers. Cloud tops may exceed 12 kilometers on some days.

During daylight hours, clouds form over the target ridge (the western ridge of the Nam Mae Tun watershed) from the combined impacts of low-level heating, orographic lifting, and perhaps the presence of a mesoscale or synoptic scale disturbance to promote convergence at low levels and, therefore, convective cloud development. All clouds forming over the rising terrain have a limited amount of time in which to produce precipitation before experiencing drying effects from subsiding airflow on the lee of the ridge. Because the distance from the foothills to ridge top averages about 15 kilometers, the time available for rain to form before the clouds begin to dissipate is some 10 to 100 minutes.

Physical hypotheses (sometimes called conceptual models) describe the expected sequence of events for treated clouds. The following paragraphs give physical hypotheses for two distinct cloud types and suggest how the clouds selected as treatment units might be induced to produce more rainfall before weakening or dissipating in the subsiding air stream to the lee of the target ridge. The two distinct cloud types currently identified as treatment units for the demonstration project are:

a. The cumulus cloud whose top never rises above the -10 °C level and does not develop significant concentrations of ice particles. For simplicity, clouds of this type will be referred to as warm clouds.

b. The large cumulus cloud whose top rises above the -10 °C level, permitting the growth of some natural ice particles and of artificial glaciation by seeding. Clouds of this type will be referred to as cold clouds.

Table 4.3 provides guidelines (subject to possible future revision when calibration information becomes available) for determination of seedability for warm and cold clouds.

Table 4.3. - Guidelines for selection of treatable clouds

Variable	Acceptance window for seeding
Warm clouds	
Radar echo	None
Cloud depth (CD)	3.0 > CD > 1.7 km
Cloud presence time before arrival at ridge top	> 15 minutes
Cold clouds	
Cloud dynamic enhancement	To be determined
Cloud radar echo duration	< 5 minutes
Cloud presence time before arrival at ridge top	> 15 minutes
Cloud top temperature (CTT)	-25 °C < CTT < -10°C
Cloud updraft strength	> 3 m s^{-1}

4.5.2 Warm Clouds. - The physical hypothesis for treated warm clouds is as follows:

a. A warm cloud with little or no evidence of imminent rain formation by coalescence and at least 15 minutes available for precipitation development prior to experiencing ridge lee effects, is seeded with a hygroscopic agent. The seeding leads to the production of large (about 40 micrometers in diameter) droplets in a concentration of about 1 L^{-1} within a few minutes after treatment. The large droplets are available to serve as raindrop embryos capable of further growth by coalescence.

b. The coalescence process accelerates as the artificial raindrop embryos grow beyond about 40 micrometers in diameter. Raindrops that can reach the ground form in about 15 to 20 minutes after seeding. Losses to evaporation below cloud base are expected to be small in Thailand, as the relative humidity between the ground and cloud base is generally high during the operational season. Therefore, most of the artificial raindrops will reach the ground.

Cloud model results indicate that warm clouds must be at least 1.7 kilometers in depth in order for seeding to yield positive results. On the other hand, the coalescence process will be well developed, naturally, if the cloud depth exceeds about 3 kilometers, so clouds exceeding this depth should not be selected for hygroscopic seeding.

The criterion indicating that no radar echoes be produced by treatment candidates is included to avoid treatment of clouds that already have a well-developed coalescence process. Warm clouds should not have progressed to the point of producing a radar echo prior to hygroscopic seeding. That is, clouds should not have developed precipitation prior to treatment, because the volumes of rain forming in a typical shower are such that no significant positive effects could be expected from seeding once the natural precipitation process is underway. In fact, the results of treating such a cloud are uncertain, as the dynamical interactions are likely to be quite complex. If radar data are unavailable, one should assume that any cloud more than 3 kilometers deep has already begun to form rain by coalescence and should not be treated (experimental units where treatment takes place and radar is unavailable will go into a separate stratification).

The criterion on cloud presence well before ridge top is included to ensure enough time for precipitation to develop before clouds experience the drying effects of subsidence on the lee side of the ridge. Presence time before ridge top is calculated primarily on the basis of cloud location and direction and speed of motion. When cloud motions cannot be observed, which is a likely situation, one can utilize the steering level winds (generally 700 mb).

Cloud modeling results did not indicate any dynamic effects due to hygroscopic seeding. Additionally, the modeling indicated that calcium chloride leads to more precipitation than does sodium chloride. From the standpoint of evaluation, it is important that the selection of warm cloud seeding agents be limited to one hygroscopic agent to avoid forcing additional stratifications and thus lengthening of the project to obtain enough cases for detection of treatment effects. The selected hygroscopic cloud treatment agent will need to be properly sized and packed so as to maintain material integrity. Cloud modeling indicates some sensitivity of treatment results to agent particle size. Combining results of the modeling studies and estimates of updraft volume flowing upward within a typical warm cumulus cloud indicates that the hygroscopic seeding agent should be ground preferably into particles of 20 micrometers in diameter and applied in amounts exceeding 1000 kilograms per cloud. The specification of particle size and agent amount per cloud will take place upon final selection of the agent, settling of details of handling and dispersion and study of calibration seeding results.

4.5.3 Cold Clouds. - The physical hypothesis describing the expected sequence of events for treated cold clouds with dynamic seeding potential is as follows:

a. Seeding with a glaciogenic agent leads to the development of nearly 100 ice particles per liter throughout most of the ascending cold cloud volume upon adequate treatment agent dispersal.

b. Ice production leads to substantial latent heat release within the cloud which increases cloud buoyancy and, locally, the updraft speed. The invigorated cloud grows taller and wider than it would have naturally, thus processing more water vapor and producing more rainfall at the ground. The rainfall duration and areal coverage will exceed the natural outcome.

Criteria for cold cloud treatment should specify a minimum level of cloud dynamic enhancement, that is, of additional cloud growth due to seeding. This criterion specifies the minimum amount of cloud growth that is expected to yield beneficial amounts of rainfall from seeding. Other seeding programs have employed minimums of about 0.5 to 1.0 kilometer. The appropriate minimum dynamic enhancement for Thailand should be determined in studies conducted for this purpose.

Currently, the most common process for determining dynamic enhancement is the use of cloud models. A model or a sounding analysis procedure should be selected and properly adapted to Thailand conditions. The procedure developed needs to be fast-running on Thai computers and require as primary input the local atmospheric sounding. The cloud modeling discussions in section 3 and in appendix A cover the use of models to estimate dynamic enhancement. Additional study is vital to select, refine, and adapt an appropriate model or sounding analysis procedure for Thailand.

The criterion that cold cloud candidates not have a radar echo for more than 5 minutes prior to treatment is included to ensure that only young, growing towers are treated. The treatment of older towers leading to enhanced rainfall is unlikely according to a study by Gagin et al. (1986). Their results suggested no treatment effects on cloud candidates having radar echoes for more than 5 minutes. Applicability of these results to Thailand appears reasonable since they were obtained for southern Florida clouds, which are similar to those in Thailand.

As with warm clouds, treatment candidates' locations should be such that at least 15 minutes of traveltime be available before arrival at the ridge line, to allow for precipitation development before the lee effects are experienced. Location estimates can be obtained with steering level wind information.

The selection criteria for cold clouds provide for treatment when top temperatures are between -10 and -25 °C. The effectiveness of silver iodide as an ice nucleant increases markedly as the temperature falls below the threshold of activity around -5 °C. Currently, it is thought that the rapid glaciation required for significant dynamic effects cannot be obtained at temperatures above about -10 °C without the use of uneconomical quantities of silver iodide.

The criterion on cloud updraft strength is included so that treatment material is not released in downdrafts or in weak updrafts where proper dispersion is unlikely and liquid water contents are more likely to be low. The restriction that updraft speeds be at least 3 m s^{-1} should ensure adequate dispersion and help eliminate the treatment of old towers. After proper training, pilots will be able to estimate updraft speed with a rate-of-climb meter installed in the seeding aircraft.

A natural process that can lead to high ice concentrations at relatively high temperatures (0 to -10 °C) is ice multiplication. This process is expected to occur in some Thailand clouds and to have important implications for cloud seeding success or failure. Studies of ice multiplication in natural clouds and how it may be affected by cloud seeding would be very desirable and should take place at some point during the conduct of the demonstration project. A requirement for the studies would be that a specially instrumented aircraft be employed together with the radar to obtain the necessary measurements.

4.6 Seeding Agents

The principal currently recognized and preferred treatment agents for cold clouds are (a) silver iodide and some of its complexes (Finnegan et al., 1984) and (b) dry ice pellets (solid carbon dioxide). Introduction of these materials, sometimes called glaciogenic agents, into cold clouds leads to the formation of additional ice crystals. Dry ice pellets create ice crystals more efficiently than silver iodide at temperatures between 0 and -6 °C, making dry ice the preferred seeding agent for work in that temperature range. Silver iodide complexes are more efficient at temperatures colder than about -6 °C. As seeding clouds with top temperatures in the range from -10 to -25 °C is proposed, silver iodide in one of its complex forms appears to be the logical choice of seeding agent for cold clouds.

Devices that release silver iodide for cloud seeding are called silver iodide generators. These generators evaporate silver iodide, either pure or in a complex form, and then allow quenching of the vapor to produce large numbers of crystals that can act as artificial ice nuclei. Silver iodide complexes can be dispersed by dropping pyrotechnic flares, which create a curtain of treatment agent, or by flying through a cloud while burning in place pyrotechnic flares or combustion generators containing some liquid solution of silver iodide (Finnegan et al., 1984), which leads to an expanding tube of the agent. The droppable units allow the placement of the curtain of seeding agent within or upwind of the important cloud volume. The droppable pyrotechnics can be designed to drop specified distances before burning out and can have a delayed ignition.

Burn-in-place flares may not achieve the desired dispersion in a timely fashion. Liquid-fueled airborne generators, though yielding more nuclei per gram of treatment agent, have similar dispersion problems. Both systems would require seeding in updrafts below the -10 °C level to provide for some dispersion during ascent of the seeding agent to the -10 °C level. In some projects this is accomplished by seeding in updrafts below cloud base; however, in Thailand cloud base is frequently below the mountain tops. Consequently, seeding with airborne generators would have to be performed in a broadcast mode above cloud base and upwind of cloud candidates. It is believed that broadcast seeding could not deliver, in the time available, the quantities of seeding agent needed to produce dynamic effects in Thailand clouds.

Silver iodide can also be released from ground-based generators. The crystals are then transported by the wind and dispersed by turbulence. Orographic lifting and convection currents are important in transporting the crystals to the necessary levels in the target clouds. Reliance on air currents and turbulence for transport of treatment agent to a distant cloud volume of interest, in desired amounts and in a timely fashion, is a serious disadvantage in seeding short-lived cumulus clouds, which are the seeding targets in Thailand.

The selection of treatment methods for cold clouds depends on meteorological and cloud conditions, terrain features, and the desired effects of the seeding. In the Thailand program, cold cloud seeding will be for dynamic responses, which in turn are expected to lead to more precipitation. Since dynamic seeding requires substantial amounts of treatment agent delivered to target clouds over a period of a few minutes, the use of ejectable flares containing silver iodide is recommended. The amount of treatment agent dispensed per cold cloud and the dispersal rate depends on the updraft size and strength and the desired concentration of ice crystals. Numerical models have estimated the numbers required for a dynamic seeding effect showing that about 50 L^{-1} are necessary in towers with precipitation and as many as 500 L^{-1} if cloud water is in cloud-sized droplets. The number employed in estimates for Thailand is 100 L^{-1}, a figure frequently used by others. The typical updraft core of a growing tower is expected to have a diameter of about 2 kilometers. While there are uncertainties about such factors as the rate of diffusion of the artificial nuclei, it is believed that the evenly spaced expenditure of about 10 flares, each containing at least 20 grams of silver iodide, as the aircraft traverses the updraft at the -10 °C level, should produce an effective dynamic response.

4.7 Development of Suspension Criteria

The establishment of suspension criteria is an important part of any precipitation augmentation project. The appropriate suspension criteria depend not only upon weather conditions and soil moisture conditions, but also upon the state of crops in the area, required outdoor activities, and social customs. For example, it may be desirable to suspend operations on certain holidays or religious festivals. In general, precipitation augmentation projects are normally suspended when it appears that additional rainfall or runoff would cause economic harm. It has not yet been possible to study the target area in enough detail to determine what synoptic weather patterns produce excessive rainfall or runoff, although it is known that tropical cyclones in the Bay of Bengal are notorious for producing flooding of low-lying coastal areas. Studies will be required to determine whether or not these cyclones pose a threat to the target area. However, in view of the possibility that someone might associate damage from a tropical cyclone in Burma or Bangladesh with cloud seeding in extreme western Thailand, it would appear advisable to suspend operations whenever a tropical cyclone was present in the Bay of Bengal. Studies of past data may reveal other situations that lead to excessive rainfall. Minor low pressure areas along the intertropical convergence zone are one possible source that should be checked.

It is also advisable to suspend cloud seeding when high winds or hail are expected. Ordinarily, these are produced by large thunderstorms that might trigger suspension criteria related to heavy rain as well as criteria related to hail and damaging winds. Normally, such storms would not be seeded in any case because they generally have very cold cloud top temperatures, well below -40 °C. Cloud models and the available evidence from field experiments indicate little dynamic effect of seeding on storms with top temperatures of -40 °C or colder, so there would be no incentive to seed them. However, it would be beneficial to specify in the operations plan that these and other storms developing nearby would not be seeded because of the possible hazards.

Suspensions related to local outdoor activities, such as harvesting and social customs, can only be specified after consultation with local officials. Additional studies of climatological data will also be needed prior to the start of the randomized cloud seeding program.

4.8 Instrumentation

4.8.1 General. - Adequate instrumentation, consisting of seeding aircraft, a radar facility, a rain gauge network, a radiosonde unit, a facsimile weather map receiver, a remote satellite recorder, and an operations center, is vital to the successful conduct of cloud seeding operations. Table 4.4 lists the field equipment expected to be available for the Thailand demonstration program. Some additions, substitutions, or deletions are possible prior to field program initiation.

Table 4.4. - Instrumentation for the demonstration project

Pressurized, turboprop, high-performance, twin-engine aircraft with standard navigation equipment, radar, and the following airborne cloud seeding support system:

Measurement	Instrument	Response	Accuracy	Resolution
Temperature	Platinum (reverse flow)	< 0.5 s	0.5 °C	< 0.1 °C
Pressure	Pressure transducer	15 ms	4 mb	0.3 mb
Dew point	Cooled mirror	3 °C s^{-1}	0.5 °C (>0 °C) 1.0 °C (<0 °C)	0.3 °C
Liquid water concentration	Hot wire (JW)	< 1 s	0.2 g m^{-3}	0.1 g m^{-3}
Rate of climb	Differential altitude	1 s	0.5 m s^{-1} (to 8 km)	0.25 m s^{-1}

S-band doppler radar system with the following features:

250-kilowatt peak power minimum
6-meter antenna providing 1.2° beam width
DEC micro VAX II computer
Color television monitor
Radar video processor
Display processor with controller
Small table-top control console
Operator's menu on video display unit monitor
Ground clutter rejection of 25 decibels or higher
Automatic velocity unfolding
Z_{DR} switch
IFF transceiver (optional)
Digital recording of data
Remote control via dedicated telephone line
Remote work station
8.2-meter fiberglass radome

Other equipment:

Rawinsonde system for upper air measurement of atmospheric pressure, temperature, humidity, and winds
Remote satellite image recorder
Radio equipment for communications among radar station, operations center, and cloud seeding aircraft
50 rain gauges with digital event recorders
DEC micro VAX II for data analysis
Microcomputers for field use and data analysis

4.8.2 Aircraft. - Discussion to this point indicates that most hygroscopic seeding will be conducted around the tops of clouds with top temperatures warmer than 0 °C. The operational requirement is for several seeding aircraft capable of hauling at least a 200-kilogram and preferably more than a 500-kilogram load, each, of hygroscopic seeding agent to at least 3 kilometers above sea level within a reasonable time, approximately 30 minutes, and of operating there for at least 2 hours. The aircraft must be equipped with transponders so that they can be tracked by Thailand air traffic control radar or the project radar.

At least one high-performance, turbocharged or turboprop twin-engine aircraft is necessary for the glaciogenic seeding. The aircraft should be equipped with standard navigation equipment, including VOR/DME, and a 5-centimeter radar set. The aircraft should be capable of easily climbing at 400 meters per minute to at least 7 kilometers, carry sufficient fuel for a 4.5-hour flight, and preferably be pressurized so that the flight crew has a reliable oxygen source. For release of silver iodide, this aircraft must have flare racks mounted that can dispense droppable flares. The aircraft should have adequate deicing equipment for safe operation in cloud. It should also have navigation equipment so that the location of the aircraft and of releases of seeding material will be known and no infringement of Burmese airspace takes place.

4.8.3 Weather Radar. - An S-band pulsed-doppler radar with polarization (Z_{DR}) capability to distinguish water drops from ice particles is recommended. As noted in section 4.1, the proposed radar site is 9 kilometers east of Omkoi along route 1099. The radar site is located to the east of Omkoi in order to provide full coverage over the western ridge, where the two target areas are located. Primary purposes for the radar include assistance in the conduct of cloud seeding operations, case studies, and physical and statistical evaluation. The doppler feature will enable some fixed-target rejection and therefore improve radar estimates by substantially decreasing the effects of ground clutter. The Z_{DR} feature will generally allow the detection of when and where in the cloud the onset of ice particles occurs. This feature will also indicate whether the cloud constituents producing the radar echo are predominantly in an ice or water state. Additionally, a better understanding of cloud kinematics and dynamics may be possible from studies that could be conducted on radar doppler information. The radar plays a key role in the performance of the statistical evaluation as can be seen in the description and discussion of hypotheses in section 4.5.

Hypotheses deal with the effects of cloud seeding on rainfall. However, accurate measurement of rainfall is difficult. While rain gauges supply point rainfall measurements, radar provides spatial sampling capability. Because convective showers such as those that occur in Thailand may have high rainfall gradients, rain gauge point measurements may easily be unrepresentative of such a pattern. More dense rain gauge networks will improve accuracy, but the cost incurred can easily become prohibitive. The use of radar to replace rain gauges completely has not proved successful because of the inability of radar to measure rainfall accurately. The problem lies primarily in the uncertain relationship between the rainfall rate (R) and the radar reflectivity factor (Z). The relationships provided in the scientific literature do not reflect storm-to-storm or even within-storm variability of drop size distributions that affect the relationship and therefore the ability of the radar to measure rainfall accurately. Other potential sources of error include equipment calibration, attenuation of the radar beam, and evaporation and advection of the rainfall as it goes from the sampling volume to the ground. It has also been found that vertical air motions within a cloud change the drop size distribution and vertical rainwater flux, leading to additional sources of radar error. Thus, radar measurements adjusted on the basis of rain gauge observations will be used to measure rainfall in the demonstration project.

4.8.4 Rain Gauge Network. - Rain gauges will primarily serve the purposes of (a) improving radar estimates of rainfall, (b) acting as a backup to the radar in the statistical evaluation in case of major radar equipment failure, and (c) providing precipitation estimates for areas without radar data (areas of beam blocking, ground clutter, or anomalous propagation). A network consisting of about 50 tipping bucket rain gauges with digital data loggers should be installed in the project area. The data loggers will enable the storage of rainfall data for as long as an entire season in individual increments of 0.25 millimeter. However, operational procedures will require that gauges be checked periodically to maintain the quality of the collected data. Gauge resolution and the digitizing of the data will allow the development of rainfall sums for periods such as 10-minute or others appropriate for specific needs. Gauges will be installed approximately according to a rectangular grid. A rectangular pattern will work well with the adjustment of radar-estimated rainfall and also the collection of data where the radar may be unable to provide information. Current plans call for two target areas, each about 30 by 25 kilometers, and containing about 20 rain gauges each spaced in rows 8 kilometers apart for a density of approximately one gauge per 60 km^2. It would be desirable to locate a few rain gauges to the east of the target areas to facilitate possible future studies of downwind effects.

4.9 Experimental Procedures

4.9.1 General. - This subsection provides a summary of important field procedures to be performed in the demonstration project. The procedures have been formulated with limited available knowledge of weather in the Nam Mae Tun River drainage area and, consequently, may be modified when more local information and analyses results become available. Generally, field experimental procedures include all of the daily tasks that go with the declaration of experimental units, performance of specified treatments, and posttreatment study of experimental units. More specifically, these procedures include (a) development of a weather forecast, (b) application of suspension criteria, (c) weather surveillance, (d) launching of aircraft, (e) declaration of an experimental unit, (f) cloud treatment, (g) posttreatment study, and (h) case termination.

Detailed step-by-step procedures for each of these items will be specified in the demonstration project operations plan. The following discussion summarizes important points, but details are left to be covered in the operations plan.

4.9.2 Weather Forecast. - A comprehensive weather forecast should be prepared each morning of the operational period and updated as conditions change. Weather forecasters will make use of available synoptic data and analyses, satellite data, local atmospheric sounding data, output of cloud model runs, and radar information. Available cloud model output may give some indications of the types of clouds expected and of the additional growth that might occur following seeding with a glaciogenic agent for dynamic effects. Information such as surface mesoscale analyses may need to be developed by project personnel. Maintenance of information updates will be vital to declaration of a second experimental unit in a single day. Cloud seeding aircraft will supply valuable weather information for maintaining updates. Assuming that no suspension criteria are triggered and the weather forecast indicates a possibility of seedable clouds over the target ridge, the project would move to "go" status and systematic surveillance of conditions over the target ridge would begin.

4.9.3 Application of Suspension Criteria. - Once the forecast is prepared, actual and expected conditions should be compared to the previously prepared suspension criteria. Operations can proceed only on those days when none of the suspension criteria are exceeded.

4.9.4 Weather Surveillance and Aircraft Reconnaissance. - Once a forecast is developed and personnel are properly briefed, weather surveillance would be maintained until the operations director declares operations over for the day. Surveillance will involve monitoring of current and forecast synoptic and mesoscale weather conditions, observer reports of clouds and current weather, project and weather service radar reports, and satellite photographs. When weather surveillance indicates that treatable clouds may be developing or are about to develop in the project area, cloud seeding aircraft will be launched on a reconnaissance mission to the project area. Aircraft will be sent to both target areas to determine if clouds are suitable for treatment. Reports from pilots and onboard scientists would be an important additional source of information for continued weather surveillance.

4.9.5 Declaration of Experimental Unit. - The declaration of an experimental unit results from a three-phase process, the first of which is the preparation of the daily weather forecast. The second phase is the launching of aircraft based on the forecast and observance of cloud development in or near the target areas. The third phase involves examination of clouds in the target areas by pilots and onboard scientists. Measurements made with the airborne cloud seeding support system and the radar would be checked against the selection criteria of table 4.2 and a decision formulated on seeding. The operations director at the project field office would assimilate all available information and make a decision regarding experimental unit declaration.

Regarding cloud visual appearance, potential candidates for glaciogenic seeding should have firm outlines and convey an impression of persistent growth as opposed to, for example, a cutoff or stratified structure. Warm clouds also should have a hard appearance, but pronounced vertical growth is not desirable as that could lead to glaciation of the cloud top. Measurements for determination of seedability of warm clouds consist of cloud top height (and consequently depth) and temperature and radar concurrence that the precipitation process is in its early stages. Cloud location and movement would be estimated along with its general appearance.

Some measurements will also be required for qualification of cold clouds for treatment. Cloud top height and temperature will be estimated by the aircraft in the case of smaller clouds producing a weak or no radar echo, but taller clouds will require information from the radar and satellite since their tops will well exceed the -10 °C level (aircraft flight level). Estimates of cloud top height by radar should take into consideration that 10-centimeter radar can only detect precipitation. Consequently, the tops of fresh, growing towers will not be detected by radar.

4.9.6 Cloud Treatment. - Once the experimental unit declaration criteria are satisfied for a cloud class and a target area is selected at random for treatment, a particular tower is chosen and checked for treatment qualification. Upon an affirmative indication, treatment is applied by the seeding aircraft. Seeding must commence within a few minutes of qualification or a nearby fresh tower must be selected. The procedure continues with adjacent towers selected for treatment until conditions change and suitable candidates within the same cloud class no longer exist or the experimental unit expires. Ideally, the aircraft seeding warm clouds should skim the tops of cloud towers approximately perpendicular to the wind shear vector. This approach will be possible in cases where the clouds are quite scattered and in cases where isolated cloud towers grow out of a deck of broken or overcast stratocumulus. Seeding at cloud base will not be possible due to safety limitations resulting from persistent low cloud bases. Broadcast hygroscopic seeding in the general area of interest should be avoided since treatment agent trajectories will be unknown. Information received from the radar station by radio will be useful in locating the active cloud areas, but the crew of the seeding aircraft would make the final decisions on when and where to release the seeding agent.

The seeding of cumulus clouds with glaciogenic agents for dynamic effects requires the release of 5 to 10 silver iodide pyrotechnic flares per cloud, each containing some 20 grams of silver iodide. The flares should be dropped from about cloud top or on passes through the cloud near the -10°C level. The seeding aircraft should penetrate the selected tower at this level, perpendicular to the wind shear vector, and commence dropping flares as the aircraft encounters an updraft exceeding 3 m s^{-1}. Flare drops on a given pass should be separated by 200 to 500 meters (lesser separation with stronger updrafts). Seeding is terminated upon reaching the updraft edge or a selected quantity (to be determined) of treatment agent is dispersed. More than one pass may be made on large clouds or clouds with very strong updrafts, that is, more than 10 m s^{-1}. Treatment parameters will be fully specified in an operations manual.

4.9.7 Aircraft Measurements. - Cloud top height and temperature and cloud width measurements will be obtained prior to, during, and after the seeding of warm clouds takes place. In the case of cold clouds, measurements will be taken of cloud top height and temperature by the combined sources of the seeding aircraft, radar and satellite. The cloud seeding aircraft will report measurements of SLW and updraft speed. Pilots and onboard scientists will report to the operations center observed notable changes in weather and cloud conditions.

Measurements of temperature, dew point, and pressure should be taken as the seeding aircraft climbs to required altitude and at other times considered beneficial to forecasting and experimental unit history. Measurements will be useful in upper air sounding determination, which in turn will aid the conduct of operations and postproject studies.

4.9.8 Collection of Rain Gauge Data. - The rain gauge data will not be available in real time during operations. It is recommended that data be obtained from the cartridges on the data loggers installed in the rain gauges by downloading into a computer approximately every 3 to 4 weeks. Data will be downloaded more frequently if problems are suspected. The data logger records each bucket-tipping event with time of occurrence. Each tip corresponds to a calibrated amount of precipitation (0.25 mm). Consequently, the system allows the development of precipitation sums virtually over any desired time period.

4.10 Estimation of Rainfall

Results from the cloud seeding for the statistical evaluation will be monitored by the rain gauge network and radar. Physical evaluation will utilize radar and some aircraft measurements. The statistical evaluation requires rain-gauge-adjusted radar rainfall amounts as the basic data source. Due to the high cost and difficulty of installing and maintaining a dense rain gauge network and the inadequate accuracy of rainfall determinations by radar alone, the use of gauge-adjusted radar rainfall measurements is recommended.

The general procedure for obtaining gauge-adjusted radar rainfall measurements starts with the development of precipitation totals of interest for the individual gauges as the data become available. Expeditious processing of the data will also help discover equipment malfunctions. Currently, the precipitation values of interest include those that match a radar volume scan period (about 7 or 8 minutes), hourly sums, experimental unit amounts (likely 3 hourly sums), and daily totals. Other sums may become desirable as studies are initiated. Adjusting the radar data requires some technique to develop correction factors, which would then be applied in some manner to the radar data.

The adjustment procedure recommended for the Thailand program to estimate volume rainfall is that developed by Brandes (1975). His approach is designed to utilize the point accuracy of gauges and the good spatial coverage by the radar. The principal steps in his technique are as follows:

1. Values of gauge-radar rainfall ratios (G/R) are developed at each gauge location employing radar data from within a distance much less than the gauge spacing for each gauge.

2. A threshold is selected for the radar rainfall data followed by its conversion to a Cartesian grid with spacing approximately that of the radar resolution.

3. The gauge data and G/R ratios are converted to the same radar Cartesian grid using the objective analysis technique of Barnes (1964). The weighting factor used in the Barnes method is suggested by the gauge density.

4. A gauge-adjusted radar rainfall field is obtained by multiplying G/R ratios and radar rainfall values.

5. A combined gauge and adjusted radar rainfall field is developed. The procedure calls for giving 100 percent weight to the gauge field when a grid point coincides with a gauge location. Otherwise, the weight for the gauge field decreases linearly with distance from the nearest calibration gauge; and the weight increases to the adjusted radar field to 100 percent at a prespecified distance.

It is anticipated that the low cloud bases (temperature of about 22 °C) and high relative humidity below cloud base will substantially lessen radar errors from evaporation and advection. Restricting the target areas to no more than about 60 kilometers from the radar will help control radar estimation errors. Fixed target rejection by the radar system should also lessen errors.

The Brandes technique will also enable the estimation of the volume rainfall. Computer software will be developed to properly archive rainfall data from the gauges for use in future studies.
It is essential to the AARRP to test whether the rainfall pattern is altered by the cloud seeding. In order to do this, rainfall must be known with resolution in time and space adequate to detect pattern changes that may result from the cloud seeding. At this point, it appears that about 20 rain gauges will be installed in each of the target areas for a density of about one per 60 km^2. If rainfall is initiated 8 minutes earlier due to cloud seeding, as some of the modeling results indicate, winds of 7 m s^{-1} (typical) would result in rainfall occurring about 3 kilometers further upwind. The gauge-adjusted radar rainfall measurements will be used to detect such pattern changes.

4.11 Data Management

A vital task of the AARRP is to preserve all data collected as part of the scientifically based demonstration project. Archived data will be employed in climatic, case, descriptive, and other *post hoc* studies. In order for a data management scheme to be effective, there must be adequate initial planning and allocation of human and equipment resources to implement and perform suitable data management. Proper handling of data should occur jointly along with the other phases of the program. Issues and procedures that require initial attention include the following: (a) selection of data to be archived, (b) selection of data formats for archival, (c) development of data quality controls, (d) development of data security measures, and (e) prescription of suitable data documentation.

Data selected for archival should include all information related to field operations including, but not limited to, radar, aircraft, rawinsonde, satellite, rain gauge, weather forecasting, weather, climate, and cloud treatment data. Any analyzed results such as those derived by processing radar data should also be preserved. Generally, any data for which program resources have been expended should be archived.

Data should be preserved in its original form or as closely as possible to it in order to correct for discovered calibration errors or enable the testing and application of new analysis techniques. Analog observations should be kept in their raw form. It is customary for data to be archived in Greenwich mean time.

The data manager should establish data quality control measures. Through consultation with equipment technicians, scientists, and other users, acceptable data thresholds, limits, and ranges should be established along with procedures to be implemented such as proper flagging of questionable values. Data collected on cassettes, floppy disks, or other media that are subject to deterioration by the elements should be processed promptly, including quality checking, and then entered into the archives. Early examination of data may discover systematic errors that should lead to equipment repair or recalibration and thus an improvement in subsequent information.

Because data may inspire and be utilized in future studies, adequate precautions must be implemented to ensure data safety. Information must be protected from harmful environmental conditions. Adequate precautions must be taken in transportation of data mediums from collection systems to the computer site. Backup copies should be made and stored in a secure facility away from original data sets.

Guidelines should also be established for each data set describing handling and processing procedures from collection to placement in archives. Guidelines should include proper documentation, identification of personnel (or positions) responsible for data handling, and procedures for data tracking from collection through archival.

Original data should never leave the selected data center. Requested information that is sent should be copies of original data. Proper documentation and recordkeeping are vital to good data management. Consequently, for each data set, a record of the following information will be maintained:

- Data collection procedures
- Variables recorded and units employed
- Data recording interval
- Period of record
- Start/stop times
- Archived data format
- Storage medium
- Retrieval procedures
- When received at data center
- Data set status (complete or specify contents)

A data inventory should be published at the end of each season. The contents should include an equipment description and operation modes, data availability status, samples of important data, tables of data inventories that specify parameters important to scientists and other requesters, and data request procedures.

Since unique collection and archival procedures are necessary for each data set, individual handling is required. Procedures have not been developed for the AARRP because the equipment has not been purchased yet, but procedures must be provided prior to the start of the demonstration project.

5. CONCLUSIONS AND RECOMMENDATIONS

The cloud modeling studies suggest that rainfall in Thailand can be increased by seeding warm cumulus clouds with hygroscopic agents, and by seeding cold cumulus clouds with glaciogenic agents to produce dynamic effects. We recommend that the possibilities be explored through a demonstration project involving randomized cloud seeding trials and supported by continued cloud modeling and other theoretical studies.

Before the commencement of randomized cloud seeding, a number of studies should be conducted to refine and finalize the project design and to aid in the development of seeding strategies. These studies are important to a more accurate determination of cloud treatment potential and to proper adaptation and application of current seeding technology. Given below are recommended theoretical and field studies. A work plan containing additional details on studies concerning cloud characteristics and precipitation is given as appendix B.

1. Some preliminary studies should be conducted to estimate more closely the number and character of seeding opportunities likely to occur per year. For example, improved estimates of the number of warm cloud opportunities would assist in finalizing the project design and in developing seeding strategies. These studies are also needed to finalize the boundaries of the target areas. Consequently, several types of data should be collected and analyzed to satisfy these objectives, as follows:

   a. Several years' worth of satellite imagery for both visual and infrared bands at the best resolution available should be obtained. These data should be analyzed for information on the diurnal and seasonal variations in cloud cover and on cloud top temperatures.

   b. Precipitation data from several stations in or near the target areas should be examined. Stations to be studied would include as a minimum Chiang Mai, Bhumipol Dam, Tak, Uttaradit, and Omkoi. Hourly data are preferable to daily records, as it is important to understand the diurnal cycle of cloud formation and dissipation over the target ridge.

   c. A few (3 to 10) tipping bucket rain gauges with data recorders should be installed on the target ridge prior to the 1989 wet season to enable the collection of fine (time) resolution data for essential studies and to obtain experience on the installation and care of the rain gauge network which is so essential to the project's evaluation. Statistical studies should be conducted on the rainfall data collected to assist in finalizing the project design and in developing the operations plan.

   d. Rawinsonde data, including both regular reporting stations and any special RRRDI soundings that may be available, should be assembled. Additionally, soundings from the project are very desirable for the development of the process to determine dynamic seedability for cold clouds. These local soundings should be obtained sufficiently in advance so that the studies can be conducted in time for results to be included in the operations plan.

e. A radar echo climatology should be prepared using regularly collected weather service radar data. Available RRRDI data should be incorporated into the analysis when possible. Additionally, an RRRDI mobile radar should be installed at the proposed radar site during May and June 1989 to collect additional data. The location and time of initiation of new precipitation echoes and the movement of echoes are of great interest. In addition, cloud top height and echo intensity histories would be of value in developing seeding strategies.

f. Surface and upper air charts should be obtained. These should be utilized in a study classifying the synoptic scale features controlling convective cloud development. This knowledge is useful to developing improved weather forecasts.

2. Some additional cloud modeling studies are required prior to the commencement of the randomized seeding. These studies are vital to the development of a dynamic seeding determination procedure and refined seeding strategies. Accordingly, additional cloud model runs and studies should be performed as follows:

a. Runs should be performed with the one-dimensional detailed microphysical model to investigate silver iodide and dry ice seeding at various locations in the cloud and at different seeding rates.

b. Further runs should be carried out with the same one-dimensional model to investigate the role of secondary ice multiplication. These results should be compared with radar observations of the evolution of ice particles in Thailand clouds. Comparisons with observations taken with cloud and precipitation particle probes on aircraft should be made, provided such measurements become available during the course of the demonstration program.

c. Model runs should be conducted with MESOCU or other appropriate fast-running model in natural and simulated seeding modes with appropriate available soundings and with local soundings taken prior to the commencement of randomized seeding. Comparisons of actual cold cloud top heights with those predicted should be performed. The selected model should be calibrated to best estimate natural clouds. As indicated previously, cloud top height measurements should be taken by radar at the proposed radar site during May and June 1989. Should models not produce satisfactory results, then a study should be conducted to develop procedures for analyzing local soundings to yield vital information for determining dynamic seedability. Procedures should be fully tested on local data prior to commencement of randomized seeding.

3. Additional cloud model runs that would be of interest and would assist in the understanding of the microphysical processes in Thailand natural and treated clouds are given below. These are secondary studies that could be conducted as the demonstration program proceeds.

a. Comparison of cloud evolution in the two-dimensional model with observed cloud evolution.

b. Additional two-dimensional model runs to investigate higher seeding rates and situations with different shear, temperature, and moisture profiles.

It is recommended that these secondary modeling studies be performed if funding and manpower resources become available. These studies could well serve some research purposes of other research groups interested in the study of tropical cumulus clouds.

In addition to performing studies with the individual data sets, the investigators, as time allows, should perform intercomparisons to improve our general understanding of the meteorological factors controlling precipitation in Thailand.

In summary, a suggested design for the demonstration project has been presented. Points of particular interest include the use of a randomized crossover design to estimate effects of seeding upon area rainfall, and the use of an S-band radar and a rain gauge network to estimate volumes of rain produced by seeded and nonseeded experimental units. A number of theoretical and related field studies have been recommended for conduct prior to the commencement of randomized seeding. Results of these studies are important to the refinement and finalization of the project design and to the development of an operations plan which includes seeding strategies. It is urgent that these studies commence as soon as possible.

Some secondary modeling studies have been suggested. As the operations plan is developed, other studies will be recommended to be performed as part of the evolving demonstration project. These supplemental studies of Thailand clouds and weather will be helpful in interpreting the results of the statistical evaluation of the demonstration project.

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APPENDIX A

Numerical modeling of clouds in Thailand

APPENDIX A

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FIGURES

APPENDIX A

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A.1. INTRODUCTION

Computer models that simulate cloud and precipitation development can provide useful information on the ability of cloud seeding to enhance rainfall. While such computer simulations cannot take the place of actual field experimentation, a number of possible seeding strategies and seeding materials, which are likely to have the greatest success, can be highlighted. These strategies and materials can then be tested in the field to determine which has the greatest impact on rainfall. In other words, cloud models can be the vehicle for developing conceptual models to be tested in a demonstration project.

There are many different kinds of computer models that can be used to examine clouds and precipitation. Due to computer limitations, no single model exists that is capable of answering all the questions that need to be asked; therefore, a variety of models should be used, each with its own strengths and weaknesses, to explore different aspects of cloud development and its susceptibility to intentional modification. The following discussion presents results from four different types of models: one-dimensional, steady-state with bulk microphysics; one-dimensional, time-dependent with detailed microphysics; two-dimensional, time-dependent with bulk microphysics; and three-dimensional, time-dependent with bulk microphysics. The one-dimensional, steady-state model has only bulk microphysics and is consequently only used to analyze a sounding for potential cloud development without much weight given to the precipitation development predicted. For instance, using such a model, the likely cloud top height for a given initial sounding can be determined. Such models run relatively quickly and allow for the analysis of many soundings. These models also provide information on a cloud's susceptibility to extra vertical cloud growth due to early glaciation of the supercooled portions of the cloud.

In section A.2 results are presented from the analysis of 13 years of soundings from Port Blair, India (on an island located to the west of Thailand), and Chiang Mai, Thailand, using a one-dimensional, steady-state model. In particular, the distribution of cloud top heights for a given sounding location will be determined, and the potential for enhanced cloud growth due to glaciogenic seeding will be estimated.

The analysis in section A.2 establishes typical soundings that characterize a given location. These typical soundings are used in section A.3 with a time-dependent, one-dimensional model with detailed microphysics to investigate various cloud seeding techniques to enhance the resulting rainfall. In particular, warm cloud seeding by hygroscopic and exothermic chemicals, and cold cloud seeding by silver iodide and dry ice, are investigated. Since two- and three-dimensional models are not practical to run with detailed microphysics, the runs from this model are used to evaluate the modification potential of clouds in Thailand to warm and cold cloud seeding.

Cold cloud seeding techniques, however, may also be investigated using bulk microphysics, such as those in the one-dimensional, steady-state model, and the two- and three-dimensional models. The two- and three-dimensional models provide a more accurate description of the cloud dynamics since effects of shear are included and should give a more accurate picture of the effects of cloud seeding on cloud dynamics than one-dimensional clouds. Detailed microphysical models, on the other hand, are likely to more accurately describe static effects of seeding, such as the development of a size distribution of particles to precipitation embryo size. The further development to precipitation-sized particles is not as reliable because of the one-dimensional constraints. Thus, only general trends in precipitation development will be noted.

In section A.4, a three-dimensional model is used to understand the interaction of the large-scale flow with the topography of Thailand. If mountain barriers are very high or small in areal extent, air tends to go around the barriers, rather than over them, which has a significant effect on precipitation patterns. Using an average July sounding and a sounding from Port Blair, the airflow and cloud development over Thailand are simulated. Because the mountain barriers in Thailand are relatively low but spatially extensive, most of the oncoming airflow goes over the mountains rather than around them. This was shown to be true for the entire country of Thailand as well as over the proposed project area. This behavior results in the formation of clouds and precipitation just upwind of most of the barriers in Thailand. These results show that it is reasonable to model the formation of clouds and precipitation over mountains in Thailand (such as those in the project area) using two-dimensional models, especially since the wind shear is mainly two-dimensional, with southwesterly flow in the low levels and northeasterly flow at upper levels. Since three-dimensional runs are relatively expensive, it was decided to test the effects of glaciogenic seeding of clouds in the project area using the less expensive one- and two-dimensional models.

Section A.5 presents results of two-dimensional model bulk microphysics runs for the typical soundings presented in section A.2 for cases of natural and glaciogenic seeded cloud and precipitation development. These runs also include topography as in the three-dimensional runs but at a particular cross section. Surface heating is also simulated. These runs are expected to give the most reliable estimate of precipitation amount and distribution in space during both natural and seeded runs.

A.2 ONE-DIMENSIONAL, STEADY-STATE MODEL WITH BULK MICROPHYSICS

A.2.1 Description of the Model

A number of one-dimensional, time-independent models have been developed in the past for various purposes. The model we decided to use was MESOCU (Kreitzberg and Perkey, 1976), a model which is well documented and has the capability of including modification of the sounding by mesoscale lifting, and by the cloud itself. In using this model, a mesoscale lifting of 0.2 m s^{-1} was included in order to simulate the effect of the lifting due to the orographic barrier. The model was run on all soundings from Chiang Mai, Thailand, and Port Blair, India, between April and September of 1973-1986. The main output of the model used in the present analysis is the cloud top height for a given sounding. Convective cloud base is calculated, and initial updraft conditions are specified as is the cloud radius at cloud base. The choice of cloud radius determines the entrainment of dry air into the cloud. Entrainment is modeled as inversely proportional to the radius of the cloud. Thus a larger cloud radius results in less dry air entrained and, therefore, a deeper cloud. In these runs of MESOCU, the updraft and cloud radius at cloud base is specified to be 1 m s^{-1} and 1 kilometer, respectively. Above cloud base, new values of updraft and cloud radius are calculated consistent with the effects of buoyancy, entrainment, and loading, on the updraft parcel. Thus the cloud radius varies with height, resulting in the entrainment rate varying with height also. The choice of cloud base updraft radius is very important, and was chosen to give results in best agreement with the one-dimensional, time-dependent model presented in section A.3. Further verification with field measurements of cloud top height should be done in the future in order to improve the predictions made by this model. A known weakness of one-dimensional, steady-state models (for example, Warner, 1970) is their inability to predict cloud top height and liquid water content simultaneously and accurately. In the following, we primarily discuss cloud top height, and ignore any predictions of precipitation made by the model.

A.2.2 Simulation of Seeding

The model normally freezes liquid water starting at -15 °C with all the liquid water frozen at -25 °C in a linear process. Seeding is simulated by initiating the freezing of liquid water at -5 °C and ending at -15 °C.

A.2.3 Choice of Sounding Location

As mentioned above, the soundings were taken from Port Blair, India, and Chiang Mai, Thailand. The Port Blair sounding was chosen because it represents a relatively undisturbed air mass over the ocean (Port Blair is located on a small island) before it encounters any significant land area. A special series of three hourly soundings were made at Chiang Mai, Thailand, on July 29-31, 1987, in order to document the time evolution of the atmosphere. This analysis showed that a strong inversion formed in the afternoon between 2 to 3 kilometers altitude in response to the solar heating of the upwind mountain barrier, with the height of the inversion well correlated with the altitude of the upwind barrier. Later in the early evening, the inversion was observed to significantly weaken, and the possibility of cloud formation enhanced. The development of strong convective clouds in the evening was observed on a number of days in July prior to this observation period. The observed temperature increase at this altitude is likely due to (a) direct solar heating of the barrier, (b) the latent heat released during precipitation formation over the barrier, and (c) subsidence in the lee of the barrier. In any case, the conclusion from this analysis is that the Chiang Mai sounding may not be representative of the atmospheric conditions over the barrier during periods of strong solar heating. For this reason, the Port Blair sounding, which is taken 400 kilometers upwind of the proposed project area, is included in this analysis.

A.2.4 Results

The results of running MESOCU at these two sounding locations is shown on figure A-1 in the form of a frequency plot of cloud top temperature. All valid soundings between April and September of 1973-1986 were included in both analyses. Soundings with superadiabatic layers were rejected as well as soundings with missing or insufficient data. The sounding times were 00 and 12 G.m.t., which are 7 a.m. and 7 p.m. local time, respectively. The model runs assumed that the clouds initiate from the convective condensation level for each sounding, and thus the predicted cloud top temperature is the coldest expected for a given sounding. Both sounding locations show that the most frequent cloud top temperature is in the range -10 to -20 °C. Note also that both locations show similar distributions of cloud top temperature. From the discussion above, larger differences might have been expected due to the geographic differences of the two sounding locations. However, both soundings were taken early in the evening or early in the morning, at which times influences of solar heating were small. The sequential soundings mentioned above mainly reflect the influences of solar heating on a sounding; and thus, by using the early evening or early morning sounding at Chiang Mai, these influences were not present. In general, however, a Chiang Mai sounding taken at other times of day must be viewed with some suspicion for its representativeness to clouds over the project area. The good agreement between the cloud top temperatures predicted at Port Blair and Chiang Mai during periods with only weak solar heating suggests that the Port Blair sounding represents a relatively good upstream sounding. Before using this sounding, however, the existing synoptic situation should be examined for significant spatial gradients of wind and temperature, especially at the 500-mb level, where influences of heating would be minimal.

The above predictions of cloud top height should be verified by field measurements in the project area. A preliminary radar echo study by Khantiyanan (1988) using data collected during June 1988 with the RRRDI 5-centimeter radar in the Bhumipol catchment area showed that 86 percent of the measured echo tops were in the temperature range of -10 to -20 °C, which is in good agreement with the results of MESOCU. These results are encouraging, but more data are still needed for other times of the year in order to be confident of the model predictions. In particular, the model needs to be run on the sounding taken during the data collection of the radar echo and intercompared on a daily basis.

The soundings from Port Blair within each cloud temperature category mentioned above were subjectively examined, and a representative sounding for each category was determined. The representative soundings are presented on figure A-2. Figure A-3 shows a sounding that was used as input for the three-dimensional model to be discussed in section A.4. In general, the soundings were close to moist adiabatic, suggesting preconditioning by convective activity upstream of the sounding location. The presence of significant amounts of moisture to high levels (300 mb) also suggests strong upward transport of moisture by convection, since the primary moisture source is at the surface. Such a sounding results in small amounts of convective available potential energy, suggesting that updraft strengths should be only moderate (5 to 15 m s^{-1}) compared to midlatitude convective storms (10 to 40 m s^{-1}). On the other hand, the deep moisture suggests a weak entrainment process, possibly allowing clouds to live longer than the equivalent midlatitude convective cloud, which often has to develop in a relatively dry upper level environment.

The main factor determining cloud top temperature in the present case was the presence of stable layers close to the appropriate cloud top temperature. In many cases, the model indicated that clouds would be able to grow through this stable layer if they were seeded. Thirty-five percent of the analyzed Port Blair soundings indicated vertical cloud growth greater than 1 kilometer due to seeding. The Chiang Mai runs show greater than 1 kilometer extra vertical growth in 28 percent of the soundings run. The presence of moisture above the stable layer (versus the dry layer often present above midlatitude stable layers) allowed the cloud to penetrate upward for significant distances without evaporation. This result gives support to the possibility of glaciogenic seeding for dynamic growth of these clouds.

It is important to note, however, that this model is only one-dimensional and that factors such as wind shear have not been included. All of these soundings show that there is significant wind shear occurring throughout the atmosphere with westerly to southwesterly flow at low levels and east to northeasterly flow aloft. In later sections, the effect of wind shear will be considered in the two- and three-dimensional simulations. The basic results on glaciogenic seeding mentioned above, however, are confirmed by the two- and three-dimensional runs.

Cloud base temperatures predicted by this model were close to 20 °C, which strongly suggests an active collision-coalescence process in these clouds. Results from the one-dimensional time dependent model with detailed microphysics show this to be the case in all the clouds simulated. First echo temperatures collected by Khantiyanan (1988) also show a significant fraction occurring at temperatures warmer than 0 °C, and cloud base temperatures to be in the range 19 to 21 °C.

A.3 ONE-DIMENSIONAL, TIME-DEPENDENT MODEL WITH DETAILED MICROPHYSICS

A.3.1 Description of the Model

The one-dimensional model presented in this section is significantly different than the model presented in section A.2. The main differences are the inclusion of time varying processes and a detailed microphysical description, which follows particle size categories of both water and ice and allows for their interaction. By including time, the full life cycle of a cloud can be followed from its initiation to its decay, and the inclusion of a detailed microphysical description shows the evolution of precipitation by the actual physical processes such as collision-coalescence. Starting with a cloud condensation nucleus spectrum, the formation and growth of cloud droplets and rain drops by condensation, collision-coalescence, and drop breakup are modeled in detail for 67 logarithmically spaced size categories that span a particle radius from 2 to 4040 micrometers. In addition, the nucleation, vapor depositional growth, and sedimentation of ice crystals are also modeled with 67 logarithmically spaced size categories spanning a particle radius from 14 micrometers to 28 millimeters.

The cloud is modeled as a radially symmetric cylindrical column of air with a time-independent radius in an environment at rest. A 2-kilometer cloud radius was used to obtain the following results. The model combines the vertical equation of motion, the first law of thermodynamics, the equation of mass continuity, and the equations expressing the conservation of water vapor, cloud droplets, and raindrops. All quantities are thus functions of both vertical location and time. Entrainment into the cloud is modeled by turbulent and dynamic entrainment. Turbulent entrainment occurs on the sides of a cloud as it ascends and is proportional to the updraft speed and inversely proportional to the square of the cloud radius. Since the cloud radius is kept constant in this model, this term is a constant once chosen. Dynamic entrainment occurs in order to satisfy the constraints of mass continuity imposed by assuming a constant cloud radius. Thus, below the level of the updraft maximum, environmental air is entrained into the cloud to maintain the 2-kilometer cloud radius; above the level of the updraft maximum, cloudy air is detrained into the environment. The actual calculations proceeded in the following manner:

a. An environmental sounding was specified and interpolated to all the model grid levels.

b. A pulse of excess temperature or humidity or both was introduced to the lower grid points of the model. In the present case a temperature pulse was introduced so that the sounding became dry adiabatic in the lowest 1 kilometer. The humidity was unaffected. The length of time the pulse was maintained was prescribed. The vertical motion generated by this pulse advected the temperature and humidity fields upward according to the model equations. The level at which the relative humidity exceeded 100 percent was defined as cloud base.

c. A dry nuclei spectrum, with up to 20 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 initial nuclei spectrum used in these model runs was a modified maritime spectrum from Florida, and typically yielded 300 drops per cubic centimeter at cloud base. The salty droplets were then allowed to grow for 1 minute, after which the spectrum was collapsed into the 67 water categories. Above cloud base, further development of the droplet size distribution was assumed to be primarily driven by supersaturation, and not the lower vapor pressure over a salty drop.

d. The model equations were then integrated in time using a specified time step short enough to maintain numerical stability.

The above description covers in some detail the model used for the following calculations. Further details can be found in Silverman and Glass (1973) and Nelson (1979). The hygroscopic seeding option of the model has been improved and glaciogenic seeding and secondary ice multiplication have been added. These options are discussed in more detail in the sections on hygroscopic and glaciogenic seeding results.

A.3.2 Description of a Typical Run

The following describes in detail one specific model run and some of its sensitivities to various parameters. This will be followed by the results of seeding various modeled clouds with hygroscopic and glaciogenic materials.

A cloud formed from the sounding presented on figure A-2(b), from which MESOCU predicted cloud top to be -14 °C. Figure A-4 presents time-height plots of several cloud variables as predicted by the one-dimensional, time-dependent model discussed above. The temperature pulse was kept on for the first 10 minutes of cloud growth and then turned off. Figure A-4(a) shows that the cloud top increases linearly with time until approximately 20 minutes, after which it starts to decay. Maximum cloud top height is 6.7 kilometers, which corresponds to a temperature of -10 °C. The maximum cloud liquid water occurs after 12 minutes at an altitude of 3.0 kilometers, and has a value of 2.5 g m^{-3}. Figure A-4(b) shows the rainwater field. Rain initially forms close to the time and location of the cloud water maximum, as expected. The development of significant rainwater concentrations, however, occurs at higher levels, mainly between 4 and 5 kilometers altitude.

The vertical velocity, shown on figure A-4(c), shows that a maximum updraft speed of 10 m s^{-1} is attained between 8 and 15 minutes of cloud growth, and between 3 and 5 kilometers altitude. At this same location and time, rapid development of the cloud water into rainwater is also occurring. Between 15 and 20 minutes, the updraft aloft decays rapidly to near zero, allowing the rainwater to start falling out, as shown in the reflectivity plot [fig. A-4(d)]. The decay of the updraft at this time is related to the loss of temperature buoyancy after 12 minutes due to the rapid entrainment of dry environmental air by dynamic entrainment during the cloud's active growth stage (as mentioned above, dynamic entrainment of air occurs until the maximum updraft velocity is reached, which is close to 12 minutes in the present case) and the onset of water loading after 8 minutes. These two factors contribute about equally to the decay of the updraft, and the consequent fallout of the precipitation. The drag of the precipitation and its evaporative cooling results in a downdraft near the surface just after 25 minutes in association with the precipitation reaching the ground. Peak precipitation rates of 120 mm hr^{-1} are observed near the surface for a minute or two, after which the precipitation rate falls off rapidly. Total duration of the precipitation is approximately 20 minutes, starting 20 minutes after cloud initiation. Total accumulated rainfall at the ground is just over 8 millimeters.

The evolution of the cloud droplet spectrum into rain is depicted on figure A-5 in a sequence of three-dimensional plots of radius (logarithmic scale) versus time with the vertical axis representing the log of the concentration and each row representing the spectra at a different elevation in the cloud. The sequence of plots in the left hand column represents the evolution of the water drops, while the right-hand column represents the evolution of the ice spectrum. In this case, very little ice was produced. From this plot, the water droplet spectrum broadens with altitude. This broadening is due to both the increased liquid water with altitude, resulting in the growth of the cloud droplets to larger sizes, as well as the collision-coalescence process. The concentration of cloud droplets at cloud base was 305 cm^{-3}, with a relatively wide dispersion with the largest drops out to 28 micrometers in radius. Since the collision-coalescence process requires the existence of cloud droplets at least 20 micrometers in radius, collision-coalescence is possible almost from the beginning of this cloud. The process is relatively slow at first because of the low liquid water contents. As the liquid water concentration increases to values above 1 g m^{-3}, the process becomes rapid.

Figures A-4 and A-5 show that the cloud goes through most of its life cycle in about 30 minutes, consisting of an active growth period for the first 20 minutes, and rainout during the last 10 minutes. This behavior is in good agreement with cloud observations taken in nonsheared environments in the tropics. The precipitation efficiency of this cloud was 19 percent, meaning that

19 percent of the condensed water reached the ground as precipitation with the rest being lost to evaporation. In the following, results are presented of a sensitivity study on this particular cloud; the study reveals sensitivity to cloud condensation nucleus spectrum, water loading, entrainment, collision-coalescence process, duration of the temperature pulse used to initiate motion, and seeding with an exothermic chemical.

A.3.3 Sensitivity Study

A.3.3.1 Continental Nuclei Spectrum. - As mentioned above, the initial cloud condensation nuclei spectrum was a modified maritime spectrum, resulting in a relatively broad distribution with cloud droplets of sufficient size to initiate the collision-coalescence process. Continental nuclei spectra have much higher concentrations than maritime spectra, resulting in larger numbers of nuclei activated to cloud droplets. These larger numbers cause the mean droplet size to be smaller and the distribution to be narrower. These two factors tend to inhibit the collision-coalescence process. Results from a model run using a typical continental nuclei spectrum, which resulted in 773 drops per cubic centimeter at cloud base, show little difference if compared only to the outlines of the two cloud water fields. On closer inspection, however, significant differences are apparent. For instance, the peak liquid water content in the continental case occurs 1 kilometer higher and 4 minutes later than the modified maritime run. The value of the maximum water content is also 30 percent greater than the modified maritime run. The peak rainwater content occurs 4 minutes later and reaches the ground 4 minutes later. These behaviors can be explained by the slower conversion to rain in the continental case due to the narrower droplet spectrum. The precipitation reaching the ground is reduced in the continental case by 16 percent compared to the modified maritime case, which shows the important role in precipitation development played by the initial nucleus spectrum.

A.3.3.2 Water Loading Off. - Water loading refers to the negative buoyancy produced by the drag of the condensed water. Turning the water loading off means setting this term to zero. Water loading occurs both from the buildup of cloud water and rainwater. Water loading usually becomes important in the mature and decaying stages of the cloud, after significant amounts of water have been condensed.

The results of turning off the water loading in the modified maritime run above were to increase the height of the cloud by 1.5 kilometers, to increase the duration and intensity of the updraft by approximately 50 percent, and to increase the amount of precipitation on the ground by 71 percent. The precipitation efficiency did not change significantly, and thus the increased precipitation was a result of more water processed by the cloud through the increased duration and intensity of the updraft. Entrainment processes were still active, and eventually the cloud buoyancy was destroyed, and the precipitation fell out. Thus water loading has a major effect on the cloud and precipitation evolution.

A.3.3.3 Entrainment Off. - To investigate the effects of entrainment, runs were made with dynamic entrainment off, with turbulent entrainment off, and with both off. Turbulent entrainment was found to have little effect on the cloud development; however, dynamic entrainment was shown to play a very significant role. With dynamic entrainment turned off, the cloud grew nearly 2 kilometers higher, liquid water contents were 50 percent higher, and the updraft magnitude and vertical extent were over 50 percent larger. The cloud also grew much faster, reaching the maximum height of the modified maritime cloud 6 minutes earlier. Because of the stronger and longer duration of the updraft, the rainwater was held up longer and consequently fell out later than in the modified maritime run. This result showed that entrainment plays an important role in the life cycle of a cloud, especially in the amount of precipitation reaching the ground.

A.3.3.4 Coalescence Off. - When a case was run with the collision-coalescence process off, the cloud outline appeared the same as in the normal run, but no rain was produced at the ground. Cloud water contents reached values 50 percent greater than in the modified maritime case, but no precipitation sized particles formed; rather, all the cloud water was evaporated back to the environment. Thus, cloud droplets are not able to grow into raindrops through condensational growth alone.

A.3.3.5 Effect of the Duration of the Pulse. - Doubling the pulse time from 10 to 20 minutes resulted in a cloud that had maximum values of liquid water, cloud height, and updraft comparable to the normal run. The duration of the cloud water, updraft, and cloud, however, was nearly doubled, resulting in nearly double the amount of precipitation on the ground. Thus, the duration of the low-level forcing has a significant effect on the total amount of precipitation reaching the ground.

A.3.3.6 Sensitivity to Seeding with an Exothermic Chemical. - The above discussion has shown that the cloud and precipitation development process is very sensitive to a number of different factors. In this section, the sensitivity of the cloud to an exothermic seeding agent, calcium chloride, is investigated. Calcium chloride is extremely soluble in water, with 74.5 grams dissolving in 100 grams of water at 20 °C. As calcium chloride deliquesces in water, significant amounts of heat are given off. The heat of solution of calcium chloride dissolved in water is -.175 kcal g^{-1}. If the deliquescence occurs in a cloud droplet, this heat is rapidly transferred to the air. If the heat given off is great enough, the buoyancy of the cloud may be affected.

In the following, the original cloud is seeded after 8 minutes of growth with 1000 kilograms of calcium chloride particles assumed to be 200 micrometers in radius. The initial dispersion of the material is assumed to occur by wing tip vortices of a C-47 aircraft following a known formula. From this dispersion, a concentration of the material is determined, which is injected into the middle of the cloud. The specific amount of chemical chosen was meant to simulate the current seeding technique of the RRRDI and roughly corresponds to phase II of their technique. Phases I and III seeding techniques were not investigated in this study because the clouds simulated did not last long enough to apply all three techniques to the same cloud. Therefore, the most promising method was chosen.

The results of the seeding show no significant effect on the cloud development. Precipitation at the ground was increased by 2 percent. This increase of precipitation is likely a result of direct coalescence growth of the injected material, since a 200-micrometer radius calcium chloride particle falls on the order of 3 m s^{-1} at 10 °C and 750 mb, based on simple calculations of terminal velocity. These particles will collide with water drops and grow rapidly to precipitation size. The updraft velocity in this seeded cloud was not significantly affected, and neither was the temperature buoyancy. In order to understand why the temperature was not significantly affected, consider a simple calculation of the temperature rise possible for a calcium chloride concentration of 1 g m^{-3}. The following expression gives the temperature rise:

$$(\text{amount } CaCl_2) \times (\text{heat of solution})/((\text{heat cap. of air}) \times (\text{density of air})).$$

For a calcium chloride concentration of 1 g m^{-3}, a heat of solution of -175 cal per gram of calcium chloride, heat capacity of air of 0.24 cal g^{-1}, and an air density of 900 g m^{-3}, the temperature rise is 0.81 °C. The observed temperature buoyancy in this type of cloud is on the order of 2 °C, which means that 0.75 °C is a significant amount. However, 1 g m^{-3} of calcium chloride is a lot of material; more realistic concentrations from the model runs are an order of magnitude less. Thus, the calculated temperature rise is only about 0.08 °C. In addition, adding large amounts of material to a cloud adds significant amounts of "loading," which significantly reduces the effective buoyancy created by any temperature increase due to the heat of solution. The vertical equation of motion (neglecting entrainment) can be expressed as:

$$dw/dt = g(D/T) - gr$$

where:

- g = acceleration of gravity
- w = updraft velocity
- D = temperature excess producing buoyancy
- T = ambient temperature in degrees Kelvin
- r = mixing ratio of the load in grams of material per gram of air

The first term on the right in the above equation represents the temperature buoyancy, and the second term on the right represents the reduction in buoyancy due to the loading produced by the weight of the material. From the previous example, D = 0.081 °C, and r = 0.1/900 = 0.000111 grams of calcium chloride per gram of air. Assuming T = 283.15 °K (10 °C), the buoyancy term has a value of 0.00286, and the loading has a term a value of 0.00111. Thus, the buoyancy created by the heat of solution is reduced by almost 40 percent due to the extra loading created by the weight of the seeding material. The net effect of the exothermic heat release on the cloud buoyancy is likely to be very small, which explains the weak effect on the cloud development observed in the model run above. More model runs are necessary, however, to verify this behavior. The role of hygroscopicity also needs to be resolved with further model runs.

A.3.4 Results of Calcium Chloride Seeding of Clouds Developed from the Soundings Discussed in Section A.2

This section discusses the seeding of one particular sounding in detail, and then mentions the results of seeding the other soundings shown on figures A-2 and A-3. Figure A-6 shows the cloud liquid water, rainwater, and reflectivity from a model run on the sounding shown on figure A-2(d), with the initiating pulse kept on for the first 10 minutes. The cloud is all warm with cloud top near 3-kilometer altitude. The duration of the cloud is slightly over 20 minutes with a small amount of precipitation developing aloft toward the end of its life. Most of the precipitation evaporates before reaching the ground in this unseeded run. Figure A-6(c) shows that no radar echo is present, at least nothing above 5 dBZ.

Figure A-7 shows the results of seeding this cloud near its top with 1333 kilograms of calcium chloride 5 minutes after initiation. The first 5 minutes of cloud water are not shown; however, the remaining outline is very similar to the unseeded case on figure A-6. The rainwater field, however, shows a significant difference. First of all, the initial seeding location shows up on this plot at 5 minutes and 2-kilometer altitude. The model considers 200-micrometer-sized particles as precipitation. The initially concentrated plume is rapidly spread out in the vertical, and so its signal disappears quickly. A dumbbell-shaped precipitation signature shows up after 10 minutes. The upper part of the dumbbell occurs in the same location and with the same magnitude as the natural precipitation signature on figure A-6(b), and is likely due to the natural evolution of the cloud droplet spectra. The lower part of the dumbbell is likely associated with the effects of the seeding material. In this case the precipitation produced by seeding reaches the ground, while the natural precipitation evaporates. The lower location of the seeded precipitation most likely reflects the faster fall velocity of the precipitation grown from the 200-micrometer particles compared to the natural precipitation. The plot of reflectivity [fig.A-7(c)] shows echo over 15 dBZ, with the first echo occurring at the same level and shortly after seeding. Thereafter, the echo spreads out in the vertical with the initial echo reaching the ground after 12 minutes. Most of this echo is likely due to low concentrations of large particles because the rainwater content in the region of most of the echo is very low.

Figure A-8 shows a seeded run the same as on figure A-7, except that the radii of the seeded particles were 20 instead of 200 micrometers. Again, the outline and structure of the cloud water field is very similar to the unseeded case [fig. A-6(a)]. The precipitation field, however, shows a significant difference from the natural and the previous seeded case. The location of the seeding does not show up in this plot as in the previous seeded case because of the much smaller particles used. The initial precipitation formation occurs at the same level as the seeding about 5 minutes after seeding. This is earlier than the previous seeding case. The initial echo, however, occurs nearly 2 minutes after this, and approximately 5 minutes later than the echo formed in the previous seeded case with 200-micrometer particles.

Results suggest that the case seeded with 20-micrometer (radius) particles has an initial precipitation field consisting of small drops without a significant radar echo. The resulting precipitation reaches the ground 3 minutes after the 200-micrometer seeded case, and produces precipitation at the ground for nearly 9 minutes, which is nearly twice as long as the 200-micrometer case. The precipitation echo shows similar structure as the 200-micrometer seeded case, except that the echo reaches the ground 4 minutes later, and the higher reflectivity zone is smaller. Overall, the case seeded with 20-micrometer calcium chloride particles produces nearly twice as much precipitation at the ground as the case seeded with 200-micrometer calcium chloride particles.

These results suggest that seeding with 200-micrometer particles mainly increases the total number of coalescence centers. If this is true, then the maximum precipitation increase for a given amount of material should occur for a seeding agent which has particles just large enough to start the collisional process. For instance, 20-micrometer particles (which are capable of direct collisional growth with cloud droplets) would create 1000 times more raindrop embryos than would 200-micrometer particles, given the same amount of material. If the seeded particle radius were 10 micrometers, coalescence growth would not occur until the nucleated cloud particles grew larger than 20-micrometer radius. When we seeded the cloud with particles of these sizes, precipitation initiated 3 to 4 minutes later, and produced 2.5 times less precipitation on the ground than the 20-micrometer case.

The above results suggest that direct coalescence growth is an important factor in the increased precipitation observed on the ground for these model runs. More model runs and field experimentation are necessary, however, in order to confirm this prediction. It should be mentioned that this type of seeding has been successfully conducted in the Caribbean Sea by Braham et al. (1957), who used a spray of water droplets as the seeding agent. Most of the seeded water drops were 100 to 300 micrometers in diameter and were released near the tops of trade wind cumulus clouds. Braham et al. (1957) found that, in order for precipitation formation to occur earlier, a large amount of water (approaching 2 m^3) had to be released rapidly (within 18 seconds) into the upper levels of the cloud. The inferred precipitation growth process was direct collisional growth of the injected water drops with the cloud droplets in the seeded cloud. In this case, obviously, the seeding agent was neither exothermic nor hygroscopic. The numerical calculations by Johnson (1980) also show that the injection of large amounts of seeding materials (on the order of tons) near cloud top with a size capable of initiating direct coalescence growth can cause precipitation to initiate earlier, consistent with the current results and the field study by Braham et al. (1957). The above discussion suggests that the primary cause of earlier precipitation formation in the case of the 200- and 20-micrometer (radius) calcium chloride particles is the direct collisional growth of these particles to precipitation.

The model was also run on the other soundings shown on figures A-2 and A-3, with results similar to those presented above. When larger clouds were seeded, the percentage increase in precipitation was smaller, a result consistent with the idea that only the seeded particles grow into precipitation, i.e., there was no Langmuir chain reaction. Further studies are needed to quantify this result more accurately.

A.3.5 Results of Glaciogenic Seeding of Soundings Which Result in Cloud Top Temperatures between -10 and -20 °C

The one-dimensional, time-dependent model was also used to test the effect of glaciogenic seeding on the development of precipitation. Only a limited set of runs has been made, but the initial results show enhanced vertical cloud growth of over 1 kilometer in a number of cases. Seeding near cloud top with 1 kilogram of silver iodide as the cloud was growing through the -5 °C level was simulated (1 kg is a large amount of silver iodide, and should rapidly glaciate the upper portion of the cloud). Further runs need to be made in order to confirm these results with more soundings and different simulated seeding rates.

A.4 THREE-DIMENSIONAL, TIME-DEPENDENT MODEL

Because simulations using three-dimensional cloud models are expensive, only a limited number of such simulations were made in this study. Despite their expense, three-dimensional simulations are extremely important, because they provide information crucial to the understanding of the interaction of airflow with real three-dimensional obstacles, which is not available in one- or two-dimensional simulations. The following presents the results of two simulations using the Clark (1977) nested-grid cloud model. The first simulation covers the entire country of Thailand and uses a mean July sounding from Port Blair, India, as the inflow boundary condition. This run was made in order to understand some of the larger scale behaviors of the mean flow in this region. The second simulation focuses on the proposed project area for the demonstration project and uses the sounding shown on figure A-4(b).

A.4.1 Large-Scale Simulation

A.4.1.1 Model Setup. - The model used in this simulation is the Clark (1977) nested-grid cloud model. The model was originally designed to simulate cloud development; but with the addition of grid nesting, the model has been extended to larger scales. In the present case, this model simulates the interaction of the large-scale flow with the country of Thailand during typical monsoon conditions. Using the mean July sounding from Port Blair, India, the model is initialized over a 1250 by 1250 by 33.6 kilometers domain. The horizontal resolution is 25 by 25 kilometers, and the vertical resolution is 0.8 kilometer. After 180 minutes of simulation time, a second, inner model is spawned, that has 0.4-kilometer vertical resolution and extends vertically to 16.8 kilometers. Horizontal resolution and domain size are left unchanged. The simulation allowed for the formation of clouds and precipitation using a bulk microphysical parameterization. An important feature of this model is the utilization of a terrain following coordinate system, which enables forcing due to topography to be simulated.

A.4.1.2 Results of Large Scale Simulation. - The mean July sounding from Port Blair, India, shows west-southwesterly flow below 7 kilometers, and east-northeasterly flow above 7 kilometers. The mean flow from the model run after 285 minutes of simulation time for the 400-meter layer immediately above the surface is shown on figure A-9(a), with contours of topography shown as the solid black lines. The main topographic features of interest are the ridge running north-south along the western border of Thailand (intersecting the southern part of the model domain near x = 600 kilometers), the mountain range running north-northwest to south-southeast in northern Burma (intersecting the northern part of the model domain at x = 1000 km), the high plateau region in north-eastern Thailand, and the isolated ridge near the Thailand-Cambodia border in the southeastern part of the domain. The topography has been filtered with a 25-kilometer wavelength filter; thus, the topography used in the model is smoothed. Note that the topography becomes steeper in the northern part of the domain. The model coordinates of the island from which the Port Blair soundings were taken are x = 0 and y = 375 kilometers. The oncoming flow interacts with the topographic features, and produces the flow pattern shown by the wind vectors on figure A-9(a). For the most part, the airflow is not significantly deflected by the orographic barrier, at least not at this height. At 800 meters above the surface [fig.A-9(b)], the airflow also shows little deflection by the underlying topography.

Recent analyses by Smolarkiewicz et al. (1988) show that the interaction of stably stratified flow with three-dimensional topographic barriers can be characterized by the Froude number, Fr, which is given by:

$$Fr = U/(NH)$$

where:

U = mean oncoming windspeed
N = Brunt-Vaisala frequency
H = mean height of the barrier

For Froude numbers above 1.0, most of the flow goes over the barrier; for Froude numbers less than 0.1, most of the flow goes around the barrier thus undergoing little vertical displacement. Intermediate Froude numbers display a complicated behavior, with upstream reverse flow occurring at Froude numbers between 0.1 and 0.55. The estimated Froude number for the situation shown on figure A-9 is close to 1.0; thus, it would be expected that most of the flow would go over the obstacle with only small lateral deflections. This is indeed the case for most of the flow shown on figure A-11. Physically, this means that the oncoming flow has sufficient kinetic energy to overcome the vertical stability force that acts to suppress vertical motions. As the flow goes over the obstacle, it also accelerates as shown on figure A-9(b). Because the airflow mainly goes over and not around the topographic features, updrafts are created just upstream of all the major ridges as shown on figure A-10(a). This plot shows the average updraft from the first model 800 m above the terrain.

As discussed above, updrafts are located upstream of each ridge and downdrafts in the lee, reflecting the development of lee waves in this region. Figure A-10(b) shows the development of lee waves downwind of the major north-south barrier. The amplitude of the lee wave decays rapidly after one wavelength. Since subsiding regions cause clouds to evaporate, regions downstream of these barriers are likely to receive less precipitation than regions upwind. The proposed project area in northwestern Thailand is in an updraft region and thus should receive ample precipitation. In the next section, three-dimensional modeling results for the proposed demonstration project area are presented.

A.4.2 Three-Dimensional Simulation of the Clouds and Precipitation over the Proposed Demonstration Project Area

A.4.2.1 Model Setup. - The model used for this simulation is the same as presented in section A.4.1.2 above but configured for a different domain. In this case, the outer model domain is 240 by 240 by 24 kilometers, and has its southwest corner located at 16.75° north latitude and 97° east longitude. The outer model has horizontal grid spacing of 4 kilometers and vertical grid spacing of 0.6 kilometer. The second (inner) model has vertical grid spacing of 0.2 kilometer and extends vertically to 6.0 kilometers; all other aspects of the model remain the same.

These two nested models were used to simulate the clouds and precipitation development for a particular sounding - July 11, 1982, 00Z, from Port Blair, India, as shown on figure A-3. The model was started at 7 a.m. local time and solar heating was simulated. The model was run for 110 minutes with the warm bulk microphysics active. The topography used for this run is shown on figure A-11(a). The lower left-hand corner of this figure shows the shoreline of the Gulf of Martaban. The ridge running south to north on the western border is located in Burma. The ridge associated with the proposed project area is located between x = 110 kilometers and x = 160 kilometers, and y = 80 kilometers and y = 160 kilometers. The highest peak in Thailand, Doi Ithanon, is located just south of the northern border of the domain at x = 160 kilometers.

A.4.2.2 Results. - A plot of the horizontal wind field 0.6 kilometer above mean sea level [fig. A-11(b)] shows that some of the flow is deflected around the main ridge in the project area. In this plot, areas that are blank represent topography higher than 600 meters. The deflection is not great, and most of the flow goes over the barrier. The Froude number for this case is smaller than in the previous simulation because the topography was not so heavily smoothed, resulting in taller mountains and consequently a smaller Froude number of 0.71. This is still a relatively large Froude number and most of the flow would be expected to go over rather than around the barrier.

The updraft field resulting from this flow behavior is shown on figure A-12(a). The thick solid lines represent updrafts and the dashed lines downdrafts. As in the previous simulation, the updrafts occur just upstream of the ridges and downdrafts form in the lee. The resulting average cloud water field 600 meters above the surface is shown on figure A-12(b), which shows clouds starting just upstream of most of the major ridges and ending just downstream of the ridges. The strongest cloud in this figure is located over the main ridge in the project area. The vertical extent of this cloud for the given time is shown on figure A-13(a), and reaches to 2.0 kilometers. An hour later, the cloud top reaches 4.5 kilometers at this location, in response to the stronger solar heating. Most of the clouds in this simulation stay below 5.0 kilometers, which is the approximate level of the temperature inversion shown on figure A-3. A notable development was the production of deep clouds to the lee of the main ridge as a result of low-level convergence in this region. The initial development of this cloud is shown on figure A-13(a), and the strong updraft produced from the low-level convergence is shown on figure A-13(b).

The maximum liquid water mixing ratio in the cloud over the main ridge shown on figure A-13(a) is located close to the ground near the peak of the main ridge. The cloud cell just to the west of the main cloud moves northeastward and eventually becomes the main cell over the ridge as the former main cell evaporates in the subsidence region downwind of the ridge. A new cell forms at the location of the original upwind cell, and the process repeats itself. The main cloud thus consists of cells moving up the ridge line and dissipating as they move downwind of the ridge. The vertical cross section of vertical velocity at this location [fig. A-13(b)] shows subsidence to the lee of this ridge on the order of 0.25 m s^{-1}.

The above discussion shows that cloud formation results as the oncoming airflow goes over the local ridges in the project area. Solar heating reduces the vertical stability of the atmosphere, making it even easier for the air to go over rather than around these ridges. The effective Froude number is increased in this case. The air interacts with the local ridges in a nearly two-dimensional sense. The wind shear, shown on figure A-3, also shows a nearly two-dimensional behavior, with southwesterly flow at low levels and northeasterly flow aloft. This is also true for most of the other soundings shown on figures A-2 and A-3. It was therefore decided to save computer time and use a two-dimensional version of the Clark model to test the glaciogenic seeding of the clouds produced from the soundings shown on figures A-2 and A-3.

A.5 TWO-DIMENSIONAL, TIME-DEPENDENT MODEL

A.5.1 Model setup

The model used for these runs was a two-dimensional version of the Clark nested grid model. The two-dimensional cross section chosen is shown on figure A-11(a) by the dashed line extending from x = 0 kilometer, y = 80 kilometers to x = 240 kilometers, y = 160 kilometers. This slice was chosen to be nearly parallel to the low level winds. Figure A-14 shows a vertical cross-section of the topographic slice used. The tall ridge shown is the main ridge in the project area. Three nested models were used. The outer model extended 240 kilometers in the horizontal and 24 kilometers in the vertical; horizontal and vertical grid spacings were 6 and 1.0 kilometers, respectively. The second (intermediate) model also had a horizontal extent of 240 kilometers but a vertical extent of only 16 kilometers, with horizontal and vertical grid spacings of 3 and 0.5 kilometers, respectively. The third, innermost model had a horizontal extent of only 150 kilometers and a vertical extent of 16 kilometers, with horizontal and vertical grid spacings of 1.5 and 0.5 kilometers, respectively. The horizontal domain of the third model started at the y = 90-kilometer position of the first and the second models. Solar radiation was simulated, with 20 percent of the incoming radiation reflected back to space. The remaining 80 percent was distributed equally between surface sensible- and latent-heat fluxes.

Four different soundings were run for 4 hours each. The soundings run are shown on figures A-2(b), A-2(d), A-2(e), and A-3. These soundings were representative of those having good potential for cold cloud development and also a variety of wind shear situations. Three different simulations were run on each sounding, each representing a different microphysical treatment. The first simulation had only warm bulk microphysics active. The second had the Koenig and Murray (1976) bulk microphysics active, using a Fletcher type ice nucleation curve. The last simulation was the same as the second except glaciogenic seeding was simulated using a modified Fletcher curve, which produces two orders of magnitude higher ice nuclei at warmer temperatures. Both of these curves show an exponential increase in ice nuclei concentration as the temperature is reduced. By -15 °C, over 10 000 ice nuclei have been activated per cubic meter by both curves. The Koenig and Murray (1976) ice parameterization divides ice into two categories - pristine crystals and graupel. Pristine crystals are nucleated from the Fletcher curve and grow by vapor diffusion and riming according to a parameterized growth rate depending on the liquid water content and the mass of the "growth mean particle." The parameterization keeps track of the number of particles per unit volume, N, and thus an average particle mass can be defined as:

$$Nm = q\rho_a$$

where:

m = average particle mass
q = mixing ratio of ice
ρ_a = density of air

The "growth mean particle" is the particle with the median particle mass for a given category of ice. Graupel particles are created when water drops collide with the pristine crystals. Growth of the graupel particles is calculated in the same way as for the pristine crystals. Fallout is calculated based on the fall velocity of the particle with the median volume radius for a particular category. Evaporation, sublimation, and melting are also calculated based on parameterized equations.

A.5.2 Results

A.5.2.1 Sounding 2b. - The sounding shown on figure A-2(b) is characterized by a stable layer between 5.5- and 7.0-kilometer altitude and a shear reversal centered near 7.0-kilometer altitude. Significant amounts of moisture exist at all levels below 9.0 kilometers. The cloud water mixing ratio from the third nested model after 75 minutes [fig. A-15(a)] shows cloud cells developing along the western side of the barrier. These cells are advected over the mountain at the speed of the mean wind, ~8 m s^{-1}, and become deeper as they approach the crest of the barrier. Precipitation forms about 15 minutes after the initiation of a cell and falls out mainly on the western side of the barrier. The precipitation reaching the ground from these small cells formed as a result of the warm rain process. Downwind of the crest, the cells gradually dissipate.

As surface heating becomes stronger, the clouds become significantly deeper; by 240 minutes, maximum cloud tops have reached close to 13 kilometers in altitude [fig. A-15(b)]. Below 6.4 kilometers, cells are still seen to be developing along the western edge of the domain just upstream of the main ridge. Aloft, however, the cloud field extends back towards the western boundary of the domain, a result of the shear reversal near 7 kilometers. Above this level, clouds developing from below are quickly sheared off and advected toward the west. The clouds in this figure are strongly tilted, even though they do not appear so because the vertical scale is exaggerated by a factor of 15 compared to the horizontal scale. The upper level cloud represents the development of an anvil cloud, which will shield the ground underneath it from solar radiation and inhibit further convection. The liquid water mixing ratio at upper levels in this cloud is unrealistically high because homogeneous nucleation of water drops was not simulated in this model. In future runs, this will be included.

The rainwater field [fig. A-16(a)] shows that rain falls over the western side of the ridge and also 25 kilometers to the east of the ridge crest. The graupel mixing ratio field [fig. A-16(b)] shows that melting ice particles also contribute to the precipitation on the ground in this region. The maximum precipitation shown at y = 155 kilometers is a result of the deep cloud at this location shown on figure A-15(b). The total cumulative rainfall after 240 minutes for the entire area is 46.5 centimeters. When this cloud was seeded as discussed above, precipitation increased by only 3 percent. Thus, glaciogenic seeding did not have a significant effect on precipitation development in this case. Since the unseeded cloud developed to cold temperatures, the ice process was able to produce significant amounts of precipitation without seeding.

A.5.2.2 Sounding 3. - The main characteristic of interest in this sounding is the strong stable layer between 4.2- and 5.5-kilometer altitude. As in the previous sounding, significant amounts of moisture exist at all levels below 9 kilometers. The vertical wind profile shows a reversal of direction between 5.5 and 7.0-kilometer altitude. The cloud water mixing ratio field from the third model after 3.5 hours [fig. A-17(a)] shows cloud development to a maximum height of only 6.4 kilometers. In this simulation, ice phase processes were very weak because of the limited vertical development of these clouds. Warm rain processes resulted in only 6.75 centimeters of precipitation reaching the ground over the domain. When this cloud was seeded, there was no detectable effect on the precipitation produced. There was also no evidence of extra cloud development in the vertical due to early freezing of the liquid water. As mentioned above, the stable layer in this sounding was very strong and likely to inhibit any extra vertical cloud growth. Thus, days with soundings that have strong stable layers are not likely to be sensitive to ice phase seeding.

A.5.2.3 Sounding 2e. - This sounding is characterized by a moist adiabatic temperature profile with no significant stable layers or inversions. Significant moisture is also present to all levels below 9 kilometers, and shear reversal occurs between 5.5 and 7.0 kilometers. Clouds below the shear reversal level at 6.0 kilometers move towards the east; and clouds above this level move toward the west, resulting in the production of an anvil (to an altitude of 12.8 km) over the low-level clouds, as shown on figure A-17(b). Total precipitation over the model domain was 19.52 centimeters after 240 minutes. The precipitation produced from the seeded simulation showed no significant difference from the unseeded run. Since this cloud developed to colder temperatures naturally, the ice process was already active; and the earlier production of additional ice crystals did not have any significant effect on the subsequent cloud and precipitation evolution.

A.5.2.4 Sounding 2d. - This sounding is characterized by a significantly lower shear level than the other three soundings presented above. Shear reversal occurs between 3.0- and 5.0-kilometer altitude. Significant amounts of moisture exist at all levels below 6.0 kilometers. Because of the low shear reversal level, developing cloud turrets are sheared off as they grow above the 3-kilometer level. This leads to a separation between the low-level cloud that is moving up the barrier from west to east and upper level cloud, which is moving from east to west. The influence of this behavior on precipitation production over the domain is significant. Over the entire domain, only 26.5 centimeters of precipitation is produced. In the seeded case, however, extra vertical cloud growth occurs, increasing the precipitation on the ground over the domain by over 30 percent. Figure A-18(a) shows the cloud water mixing ratio for the unseeded case at 120 minutes after initialization, and figure A-18(b) shows the same field for the seeded case.

The two principal clouds over the main ridge exhibit 2- to 3-kilometer deeper cloud growth in the seeded case. This extra growth is also associated with earlier freezing of the liquid water between -5 and -15 °C, as shown on figures A-19(a) and A-19(b). Note that the ice crystal concentration for the seeded case just after the initial ice forms is three orders of magnitude greater in this region. These ice crystals collide with millimeter-sized drops in this region and freeze them, releasing a significant amount of latent heat, which is likely responsible for the additional vertical cloud growth. In this case, the extra cloud growth ingests additional moist air from below, which leads to additional precipitation.

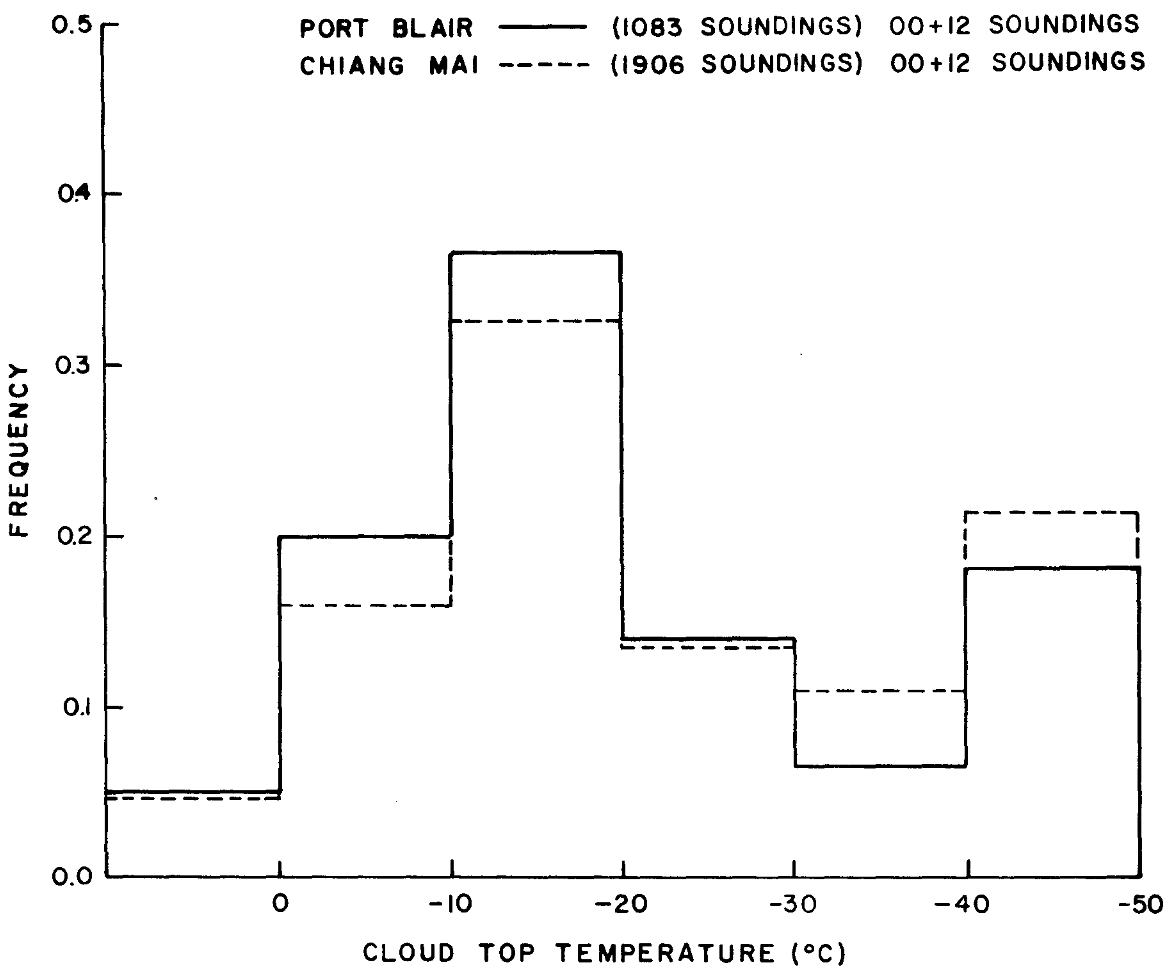
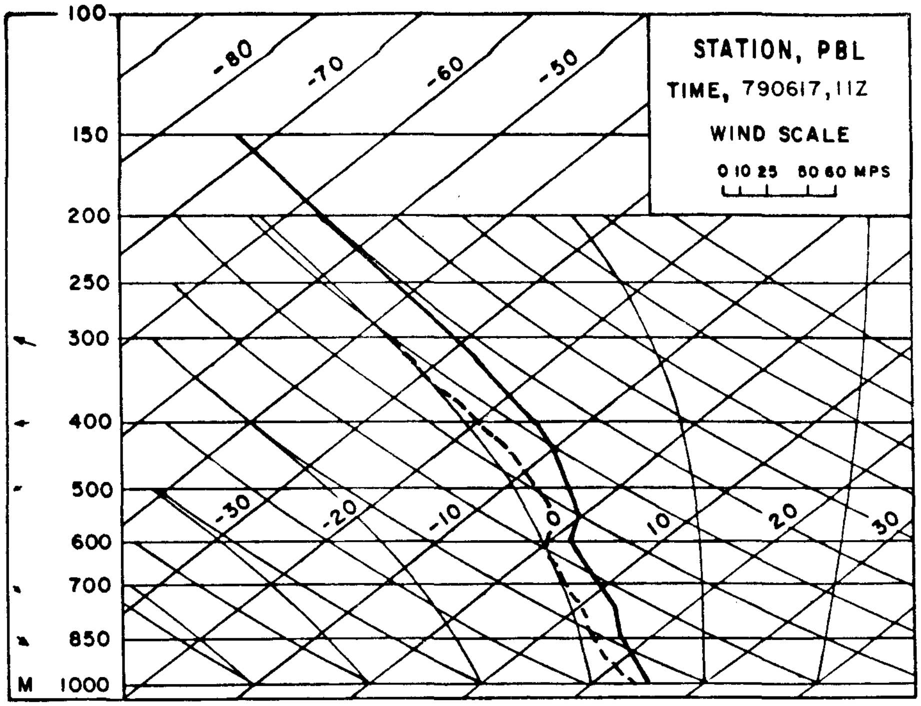
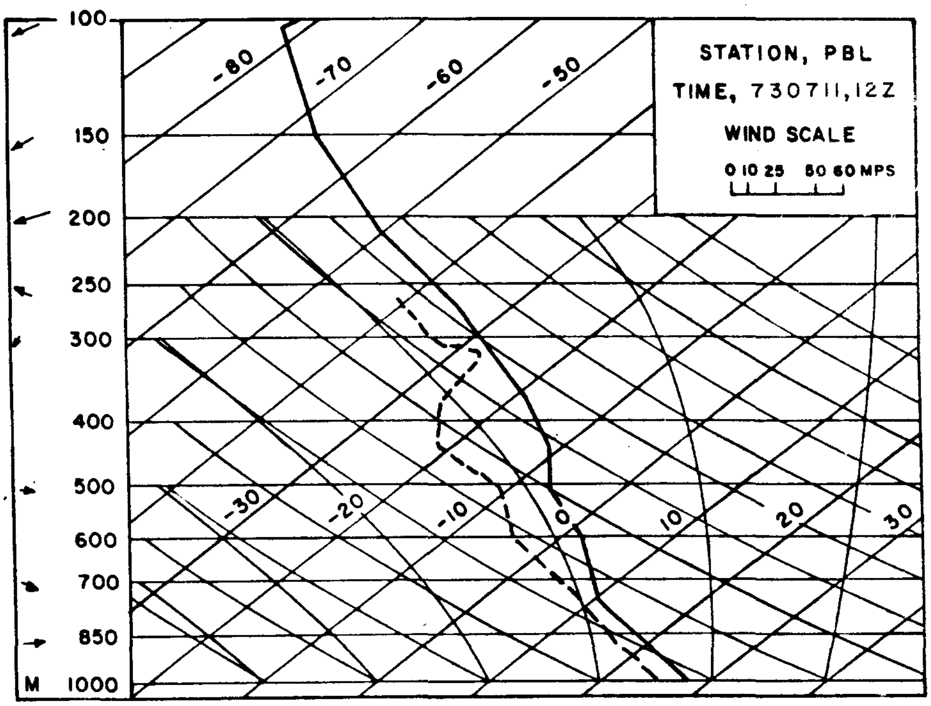


Figure A-1. - Frequency plot of cloud top temperatures derived from runs of the MESOCU cloud model.

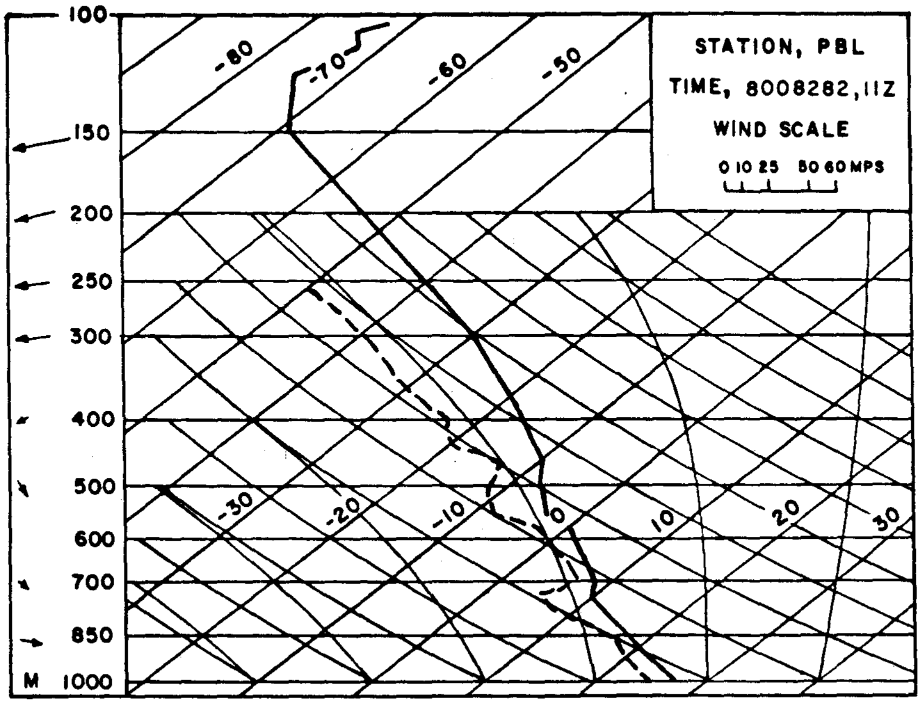


(a) 0 to -10 °C.

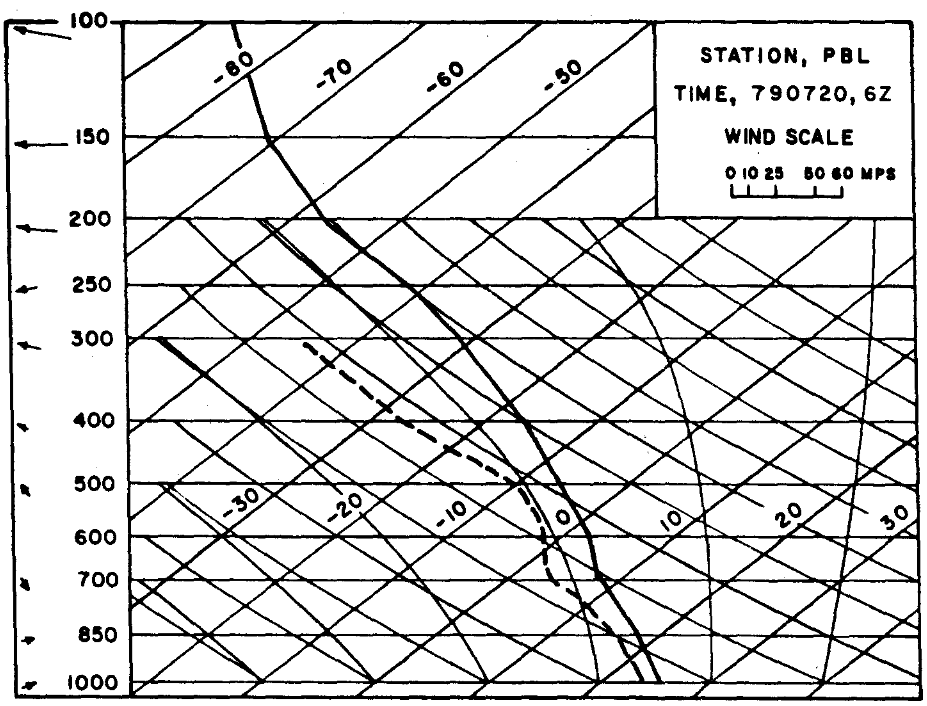


(b) -10 to -20 °C.

Figure A-2. - Representative soundings at Port Blair, India, yielding model-predicted clouds with top temperatures in ranges indicated.

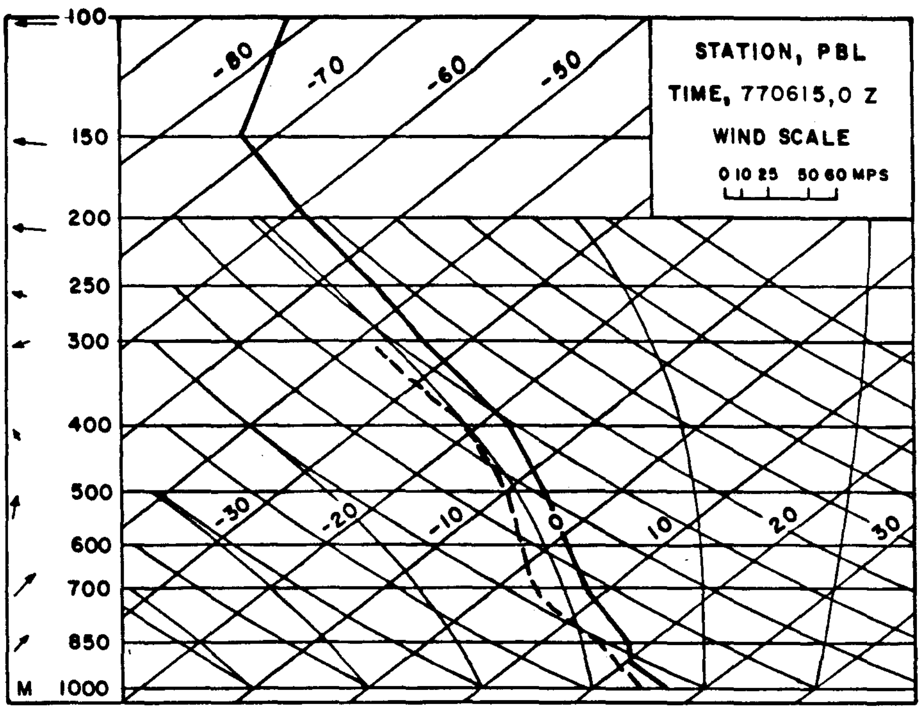


(c) -20 to -30 °C.



(d) -30 to -40 °C.

Figure A-2. - Representative soundings at Port Blair, India, yielding model-predicted clouds with top temperatures in ranges indicated. - Continued



(e) <-40 °C

Figure A-2. - Representative soundings at Port Blair, India, yielding model-predicted clouds with top temperatures in ranges indicated.

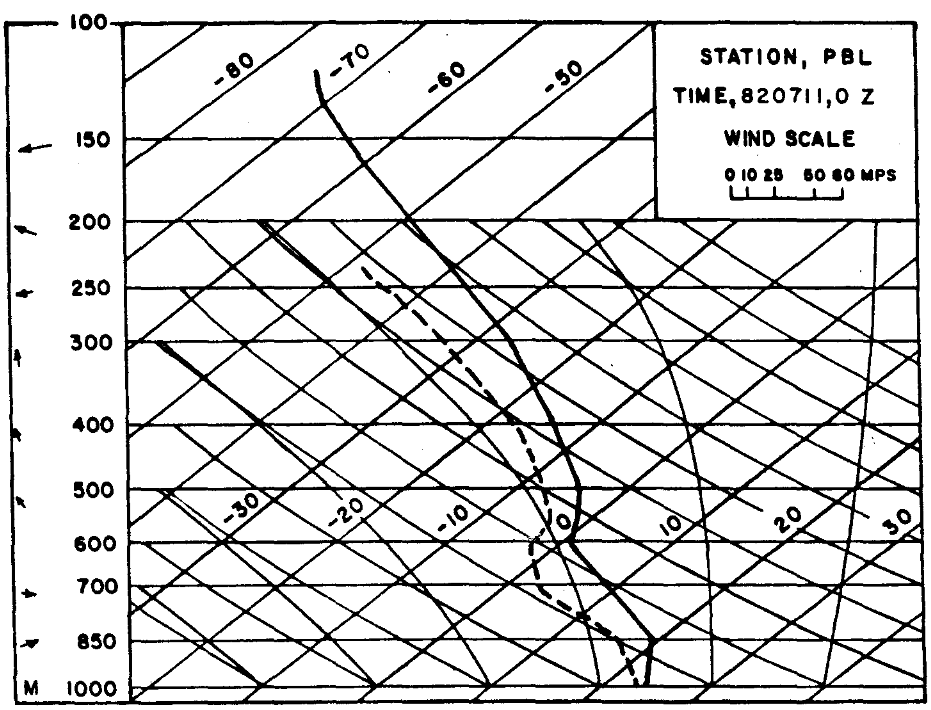
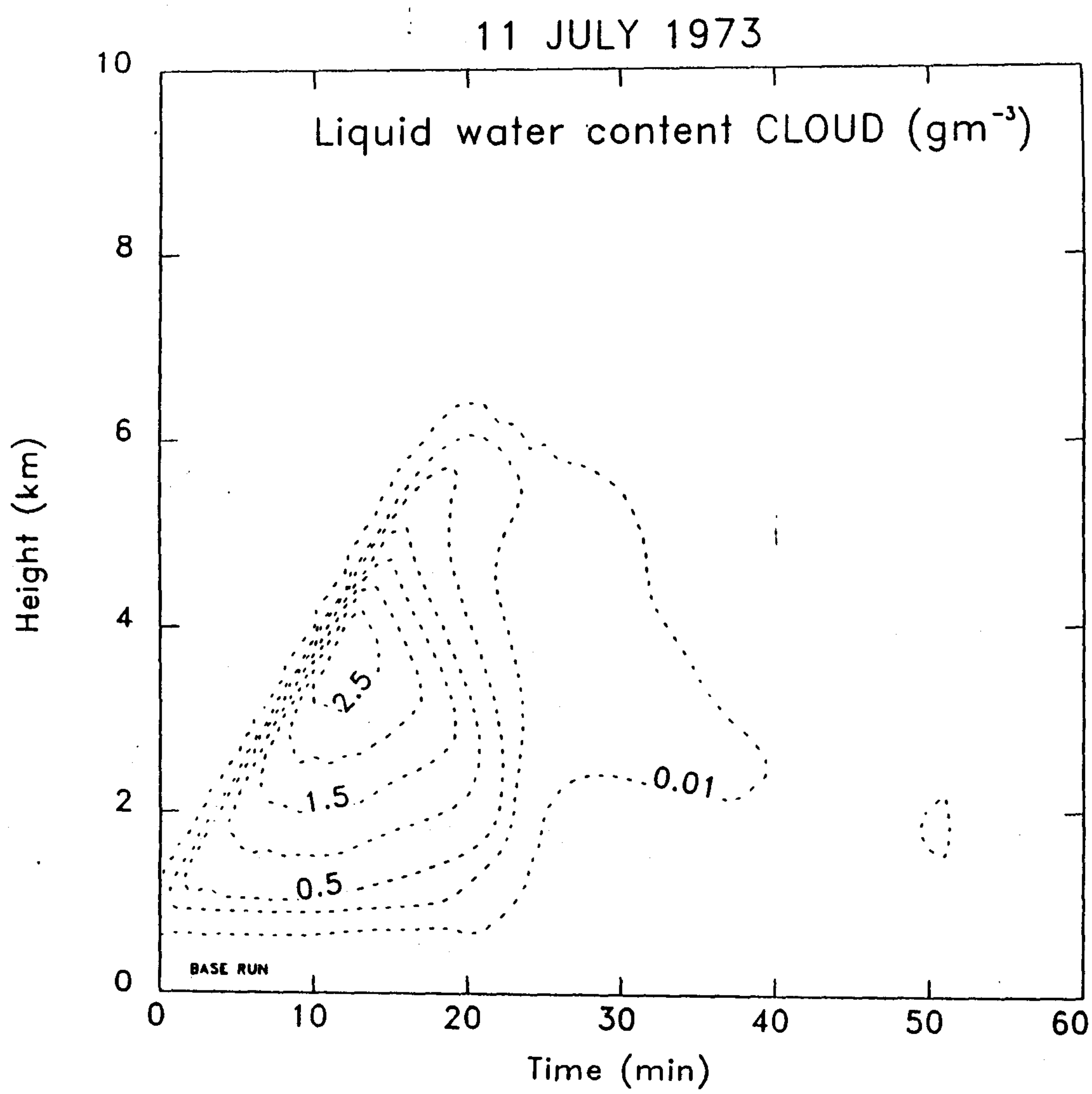
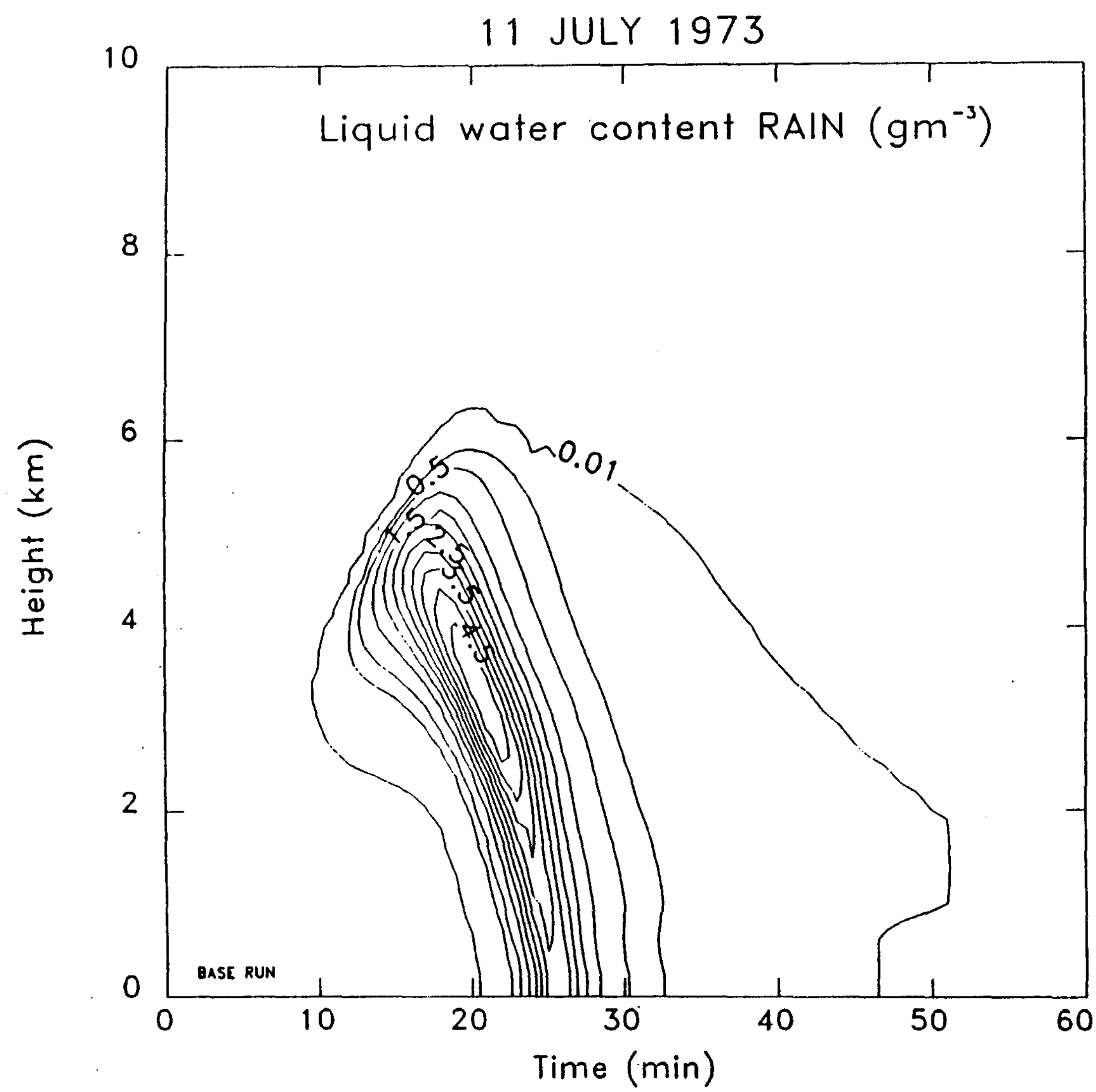


Figure A-3. - Sounding at Port Blair, India, used as input for three-dimensional model run covering project area.



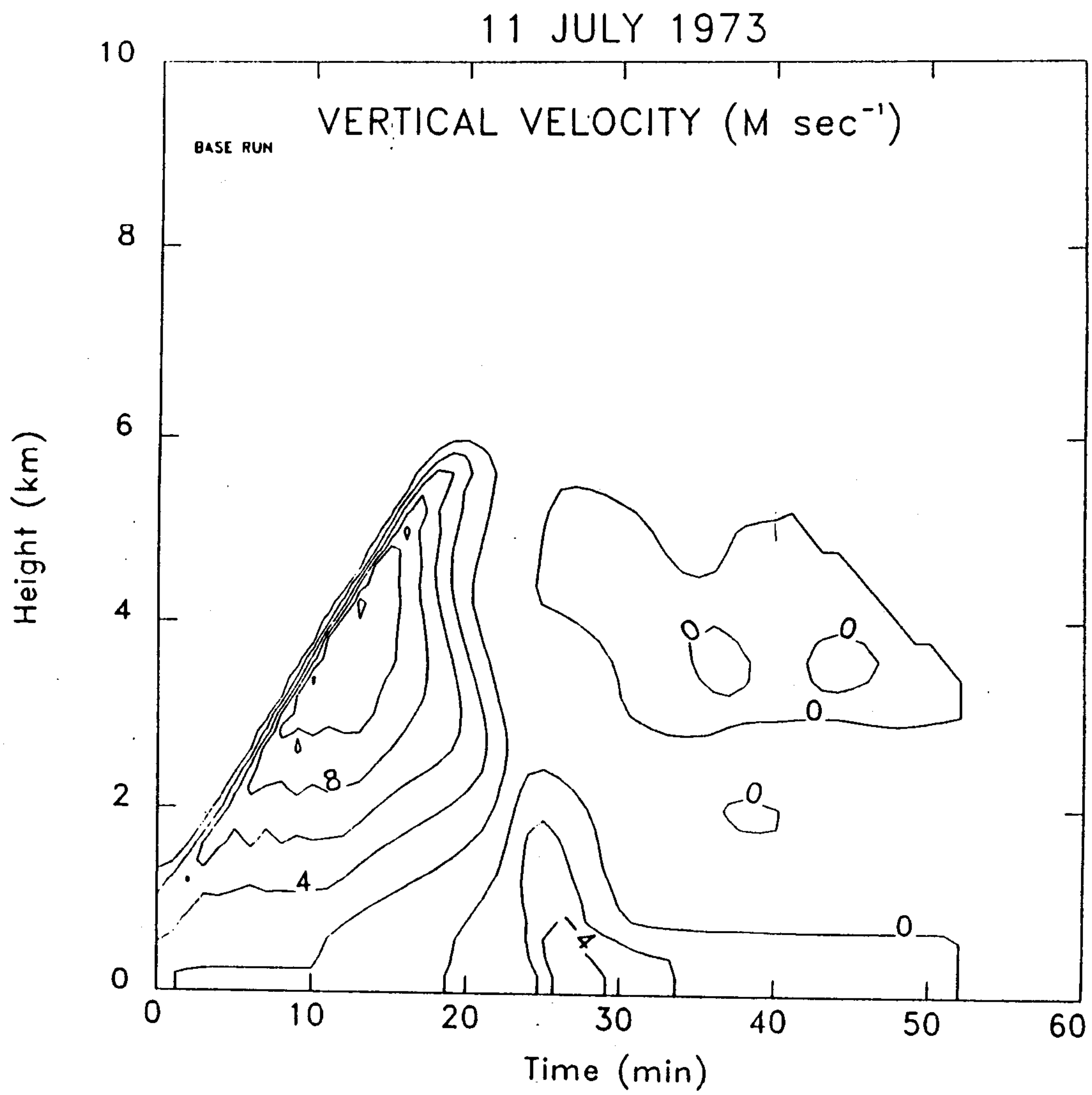
(a) Cloud water

Figure A-4. - Predicted evolution of cloud water, rainwater, vertical velocity, and radar reflectivity factor along the vertical axis of a cloud with top temperature near -14 °C.



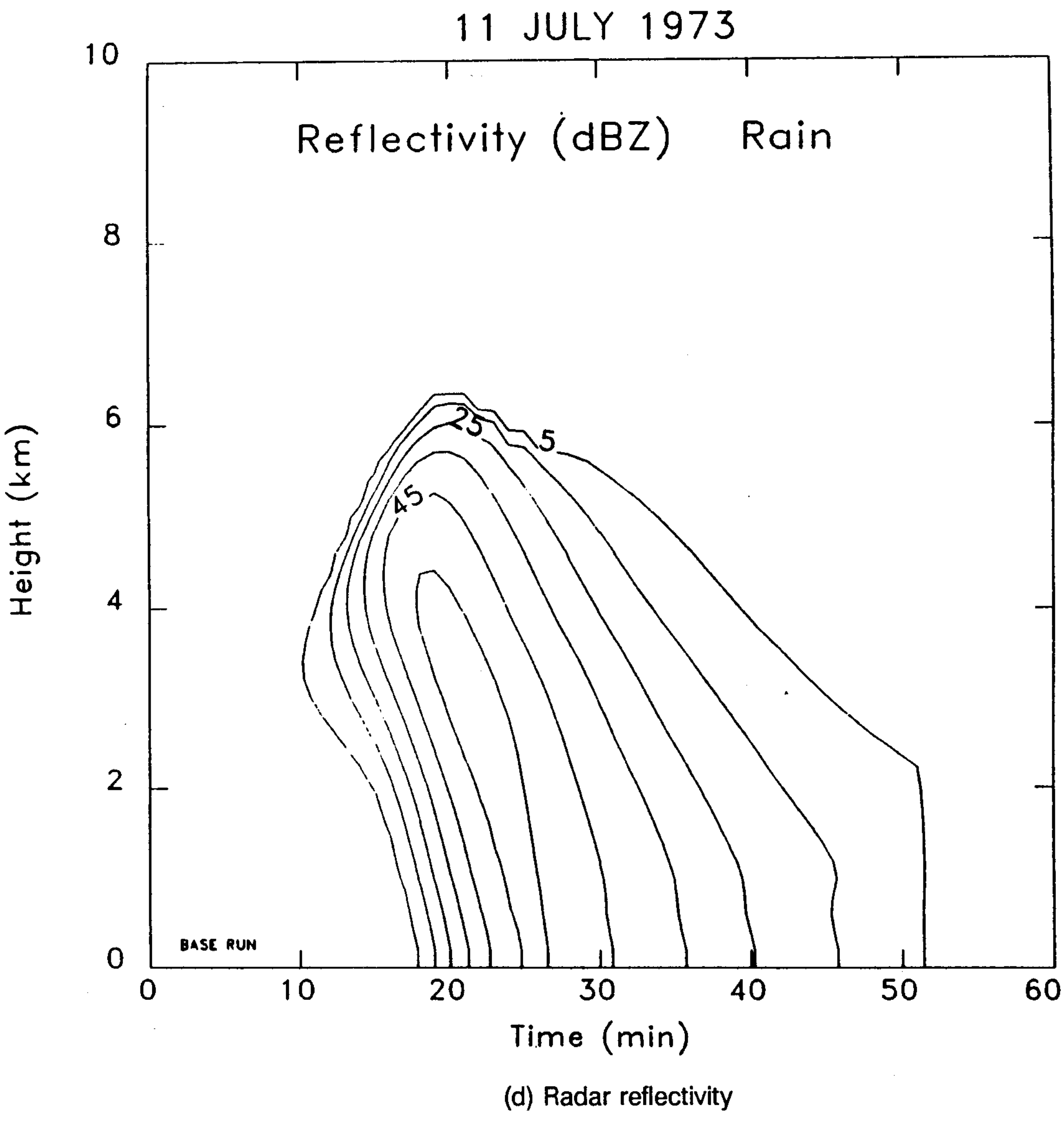
(b) Rainwater

Figure A-4. - Predicted evolution of cloud water, rainwater, vertical velocity, and radar reflectivity factor along the vertical axis of a cloud with top temperature near -14 °C. - Continued



(c) Vertical velocity

Figure A-4. - Predicted evolution of cloud water, rainwater, vertical velocity, and radar reflectivity factor along the vertical axis of a cloud with top temperature near -14 °C. - Continued



(d) Radar reflectivity

Figure A-4. - Predicted evolution of cloud water, rainwater, vertical velocity, and radar reflectivity factor along the vertical axis of a cloud with top temperature near -14 °C. - Continued

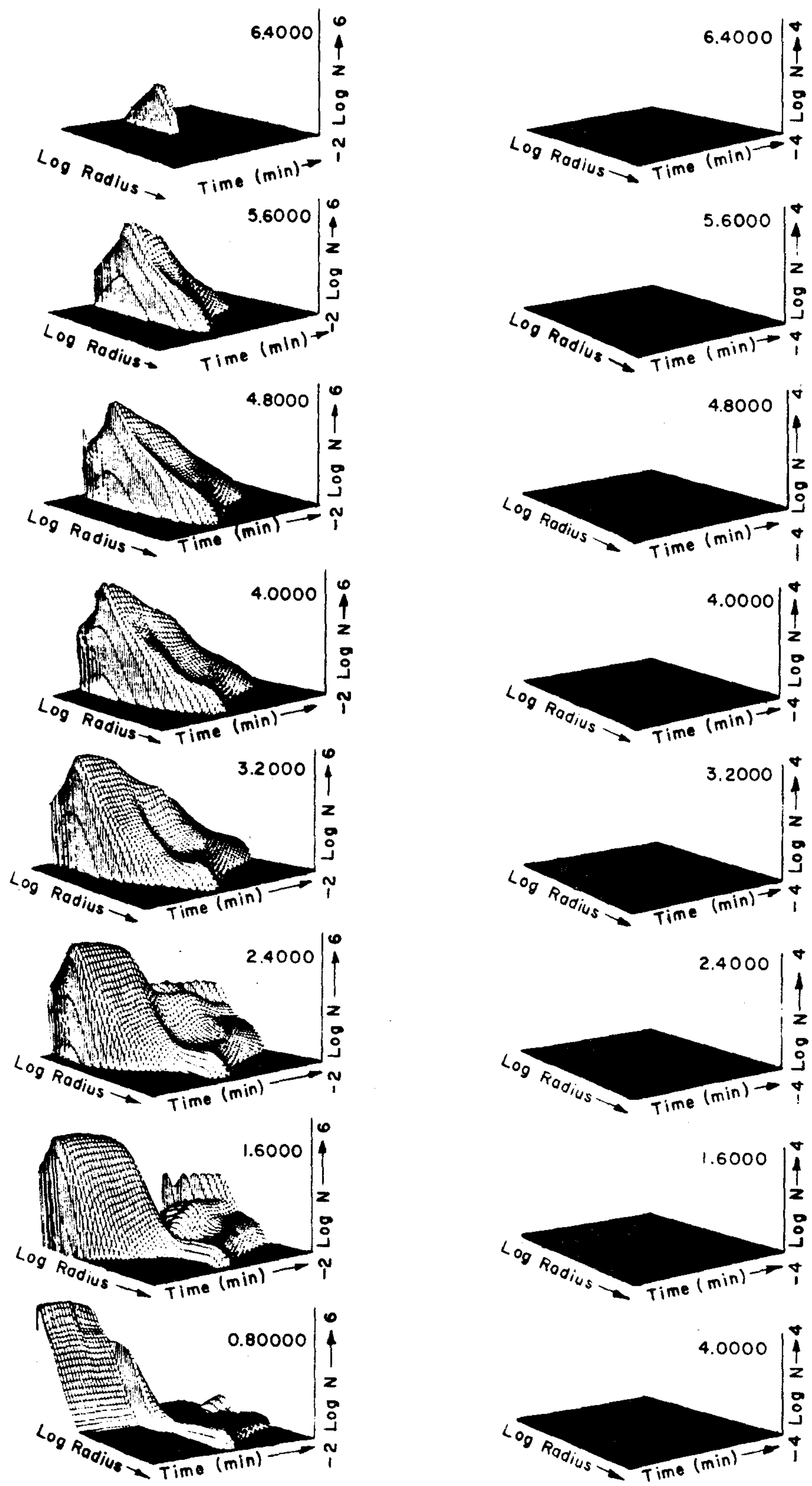
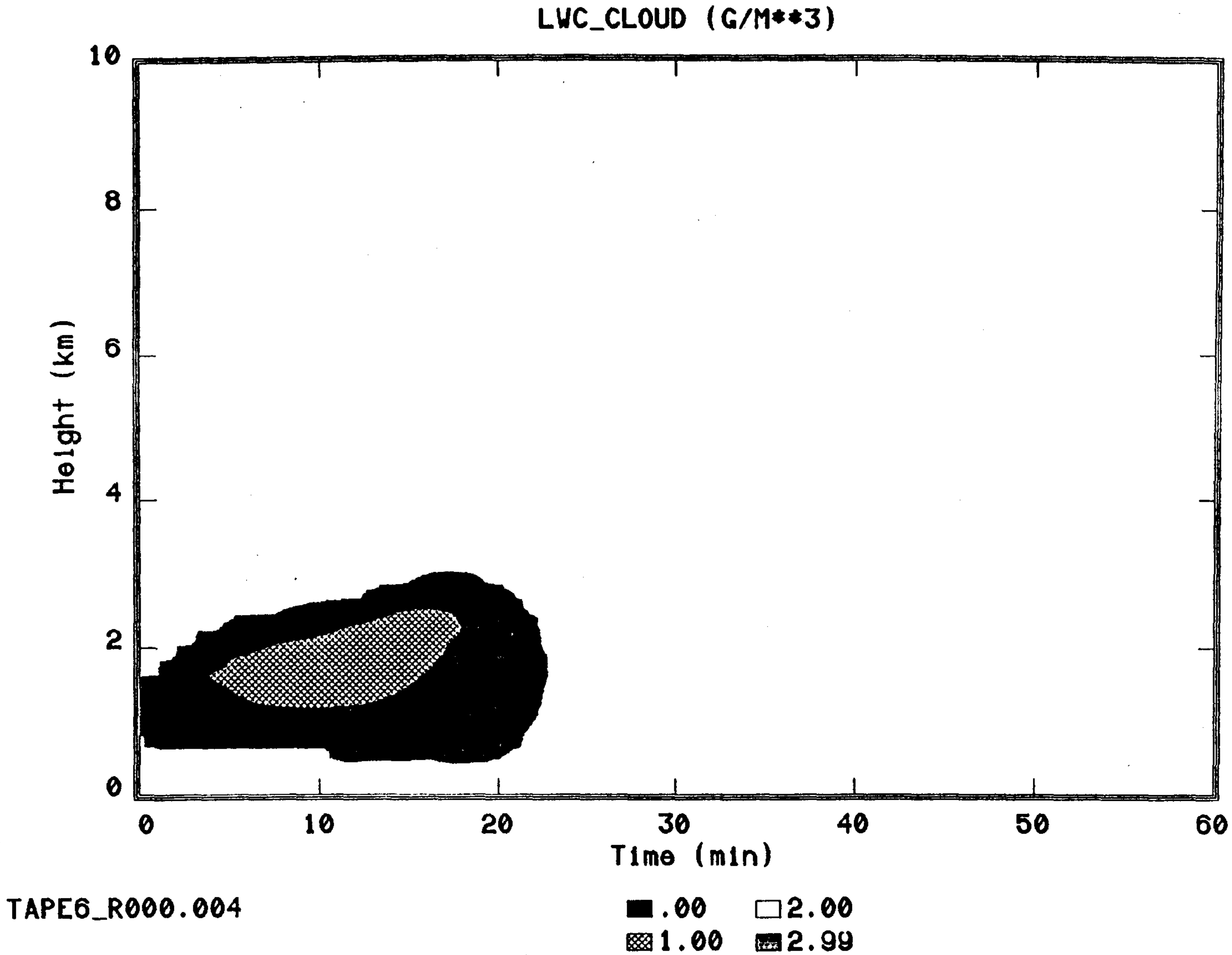
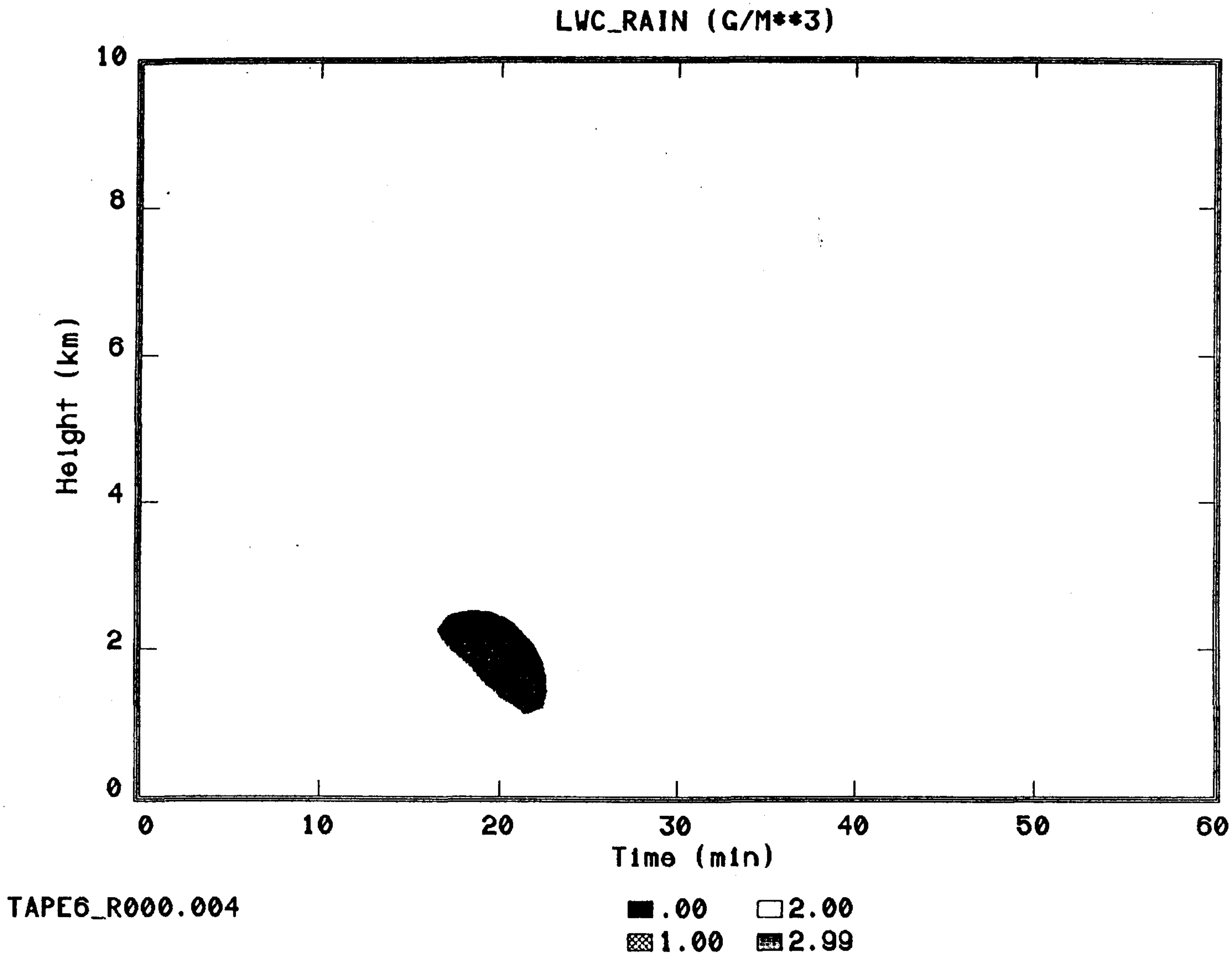


Figure A-5. - Model-predicted evolution of spectra of liquid and solid particles at various heights in cloud depicted in figure A-4. Numbers at upper right of each plot denote elevation above the ground in kilometers.



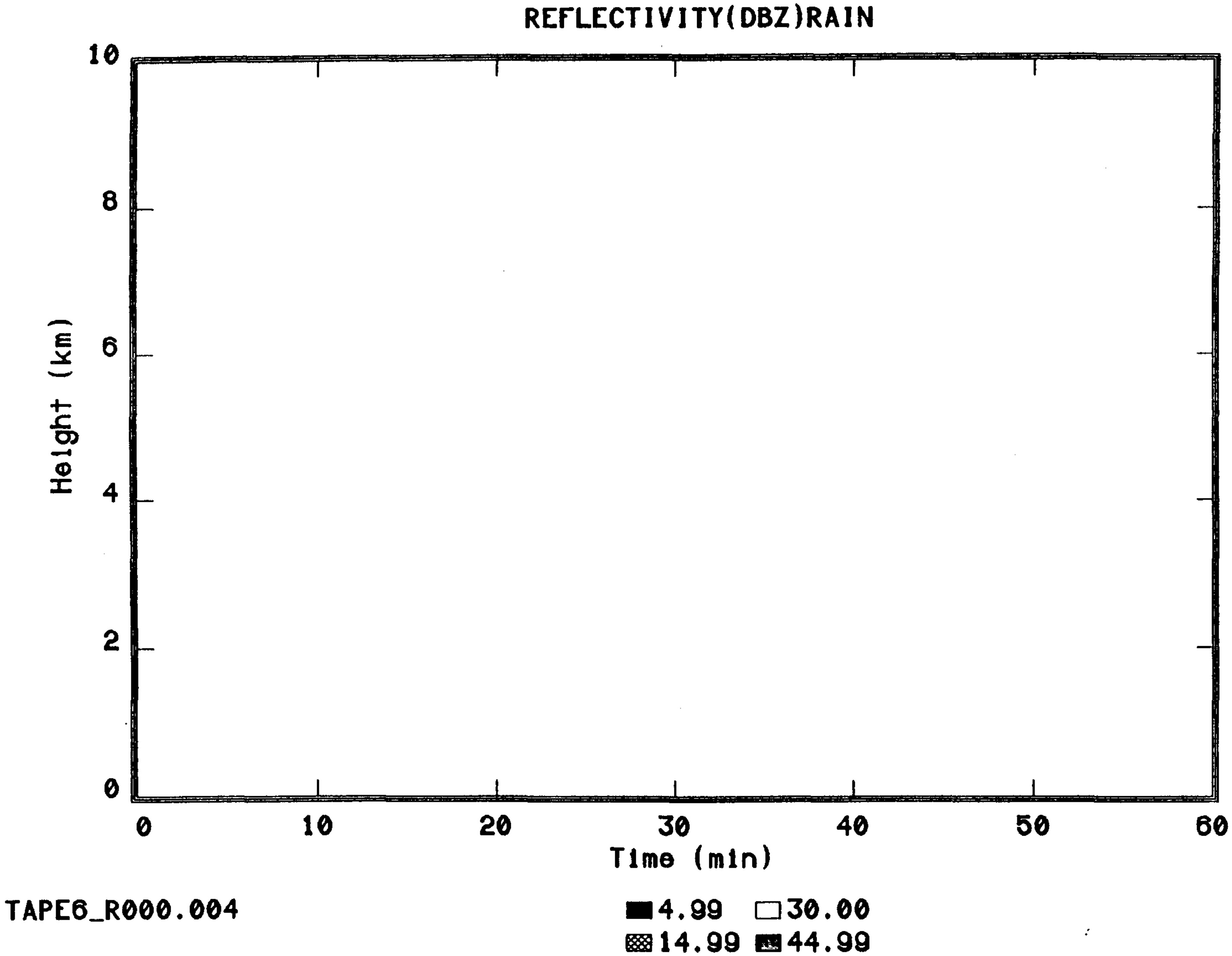
(a) Cloud water

Figure A-6. - Predicted evolution of cloud water, rainwater, and radar reflectivity factor along the vertical axis of a cloud model run with sounding of figure A-2(d) as input.



(b) Rainwater

Figure A-6. - Predicted evolution of cloud water, rainwater, and radar reflectivity factor along the vertical axis of a cloud model run with sounding of figure A-2 as input. - Continued



(c) Radar reflectivity

Figure A-6. - Predicted evolution of cloud water, rainwater, and radar reflectivity factor along the vertical axis of a cloud model run with sounding of figure A-2(d) as input. - Continued

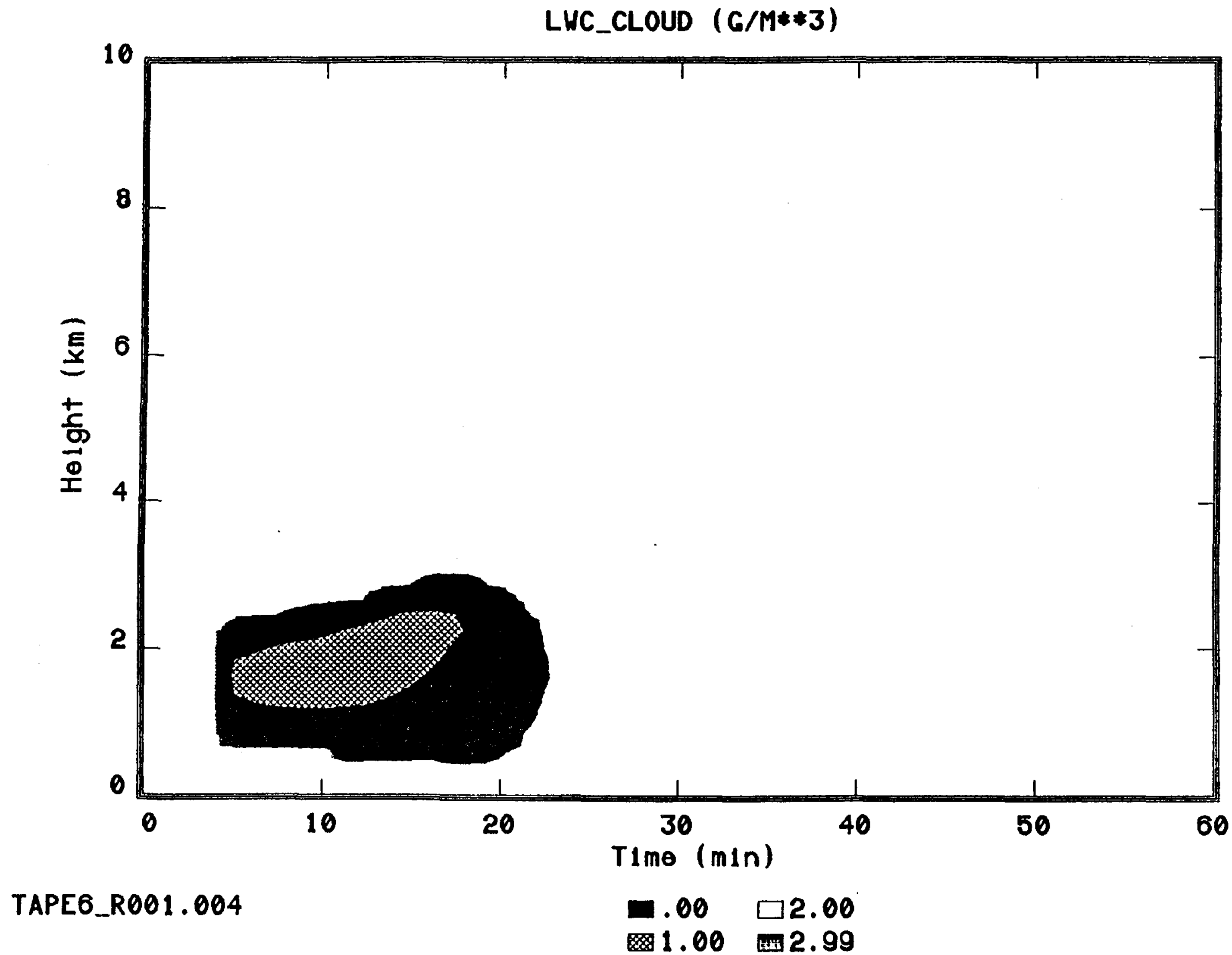


Figure A-7(a). - Same as figure A-6(a) except model run changed to simulate seeding with 1333 kilograms of calcium chloride with particle radius of 200 micrometers.

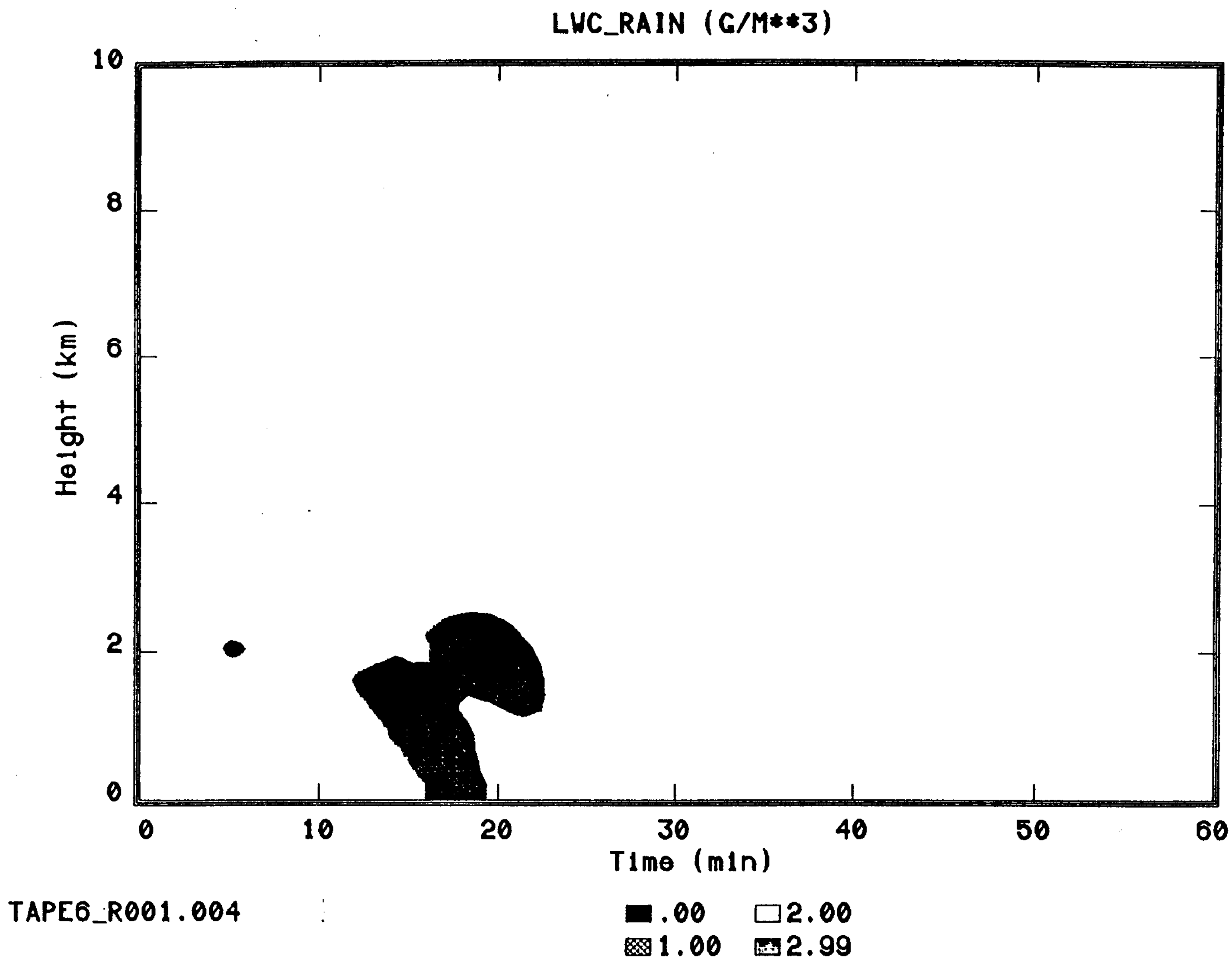


Figure A-7(b) - Same as figure A-6(b) except model run changed to simulate seeding with 1333 kilograms of calcium chloride with particle radius of 200 micrometers. -

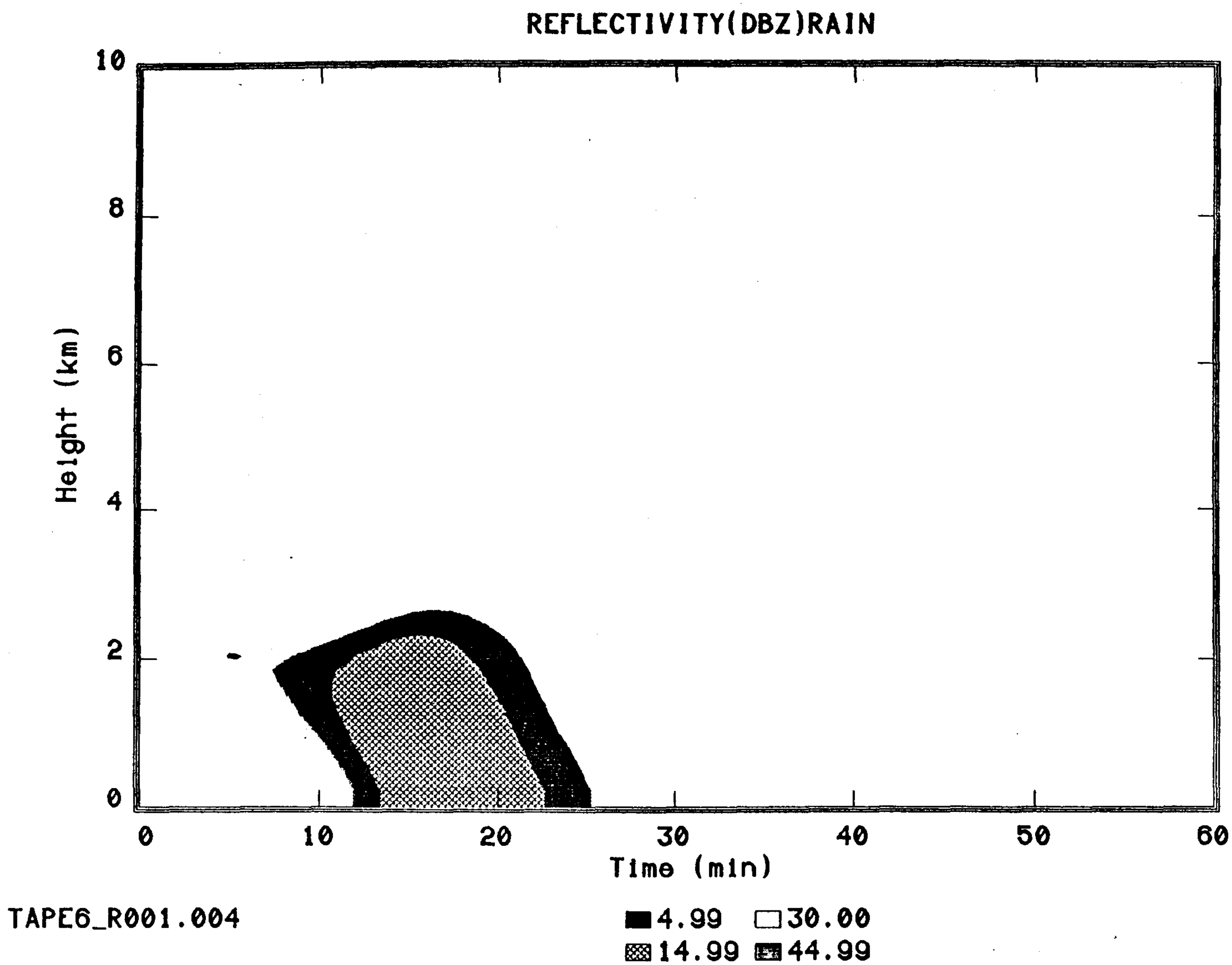


Figure A-7(c) - Same as figure A-6(c) except model run changed to simulate seeding with 1333 kilograms of calcium chloride with particle radius of 200 micrometers. - Continued

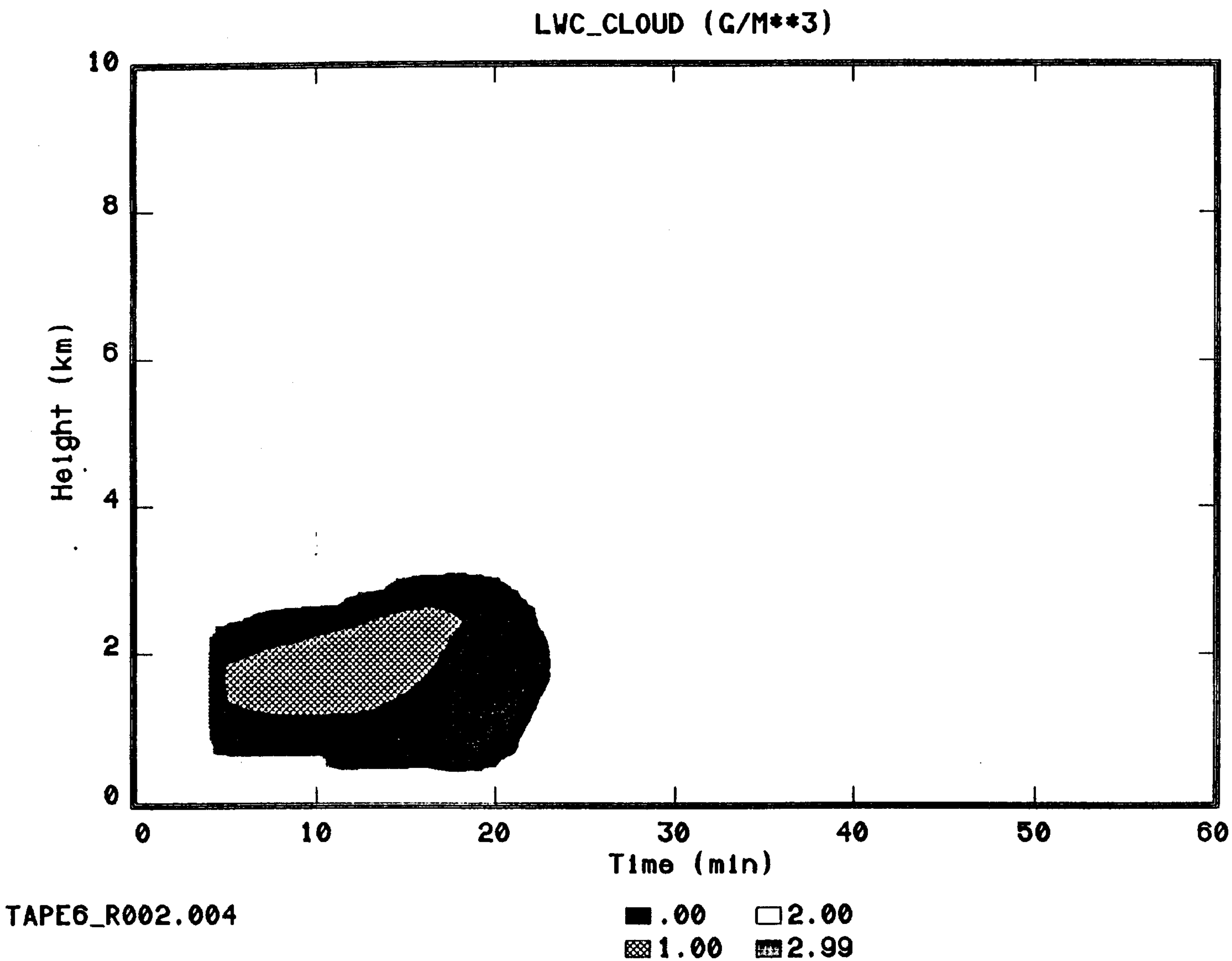


Figure A-8(a). - Same as figure A-7(a) except that particle radius is set at 20 micrometers.

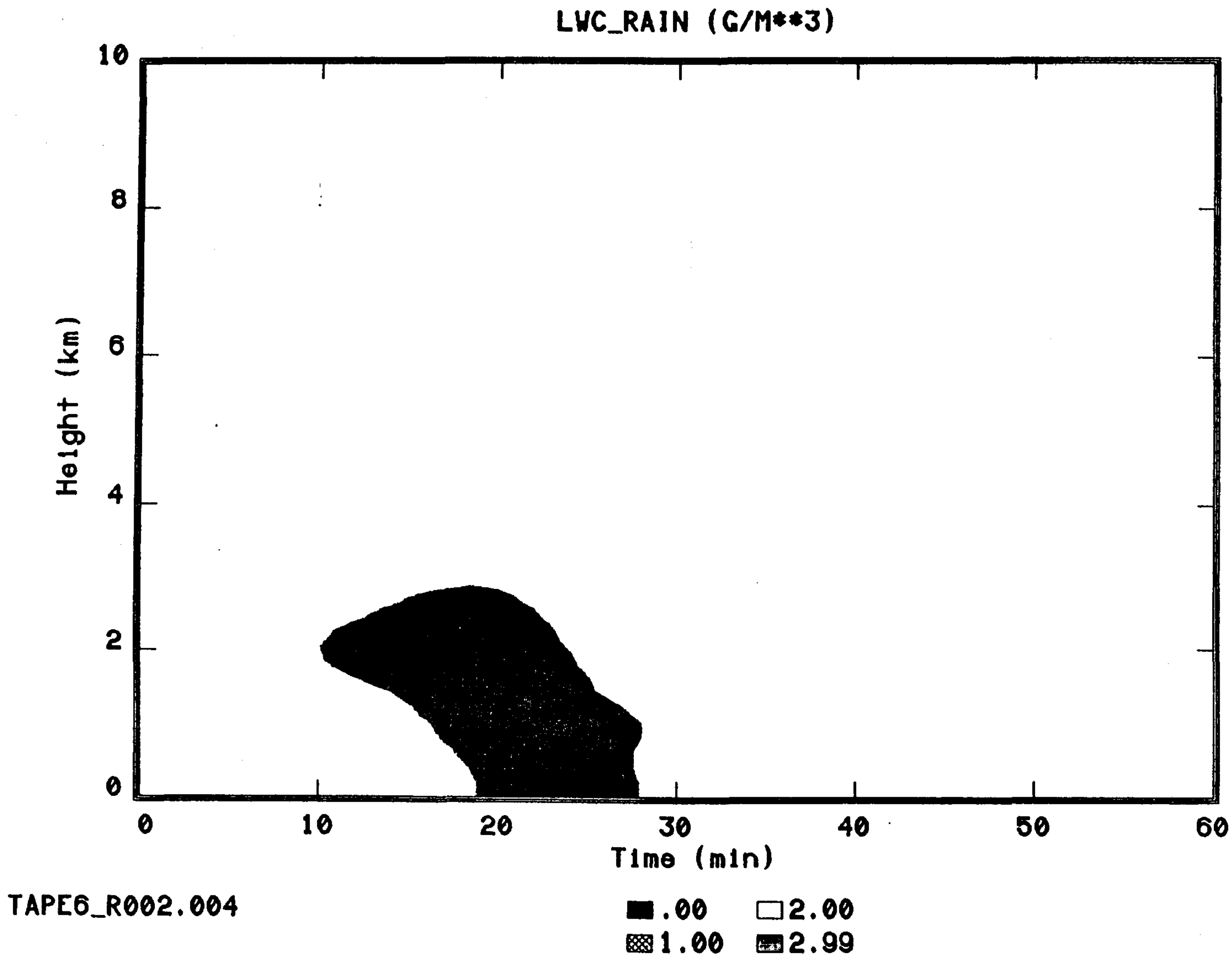


Figure A-8(b). - Same as figure A-7(b) except that particle radius is set at 20 micrometers.-
Continued

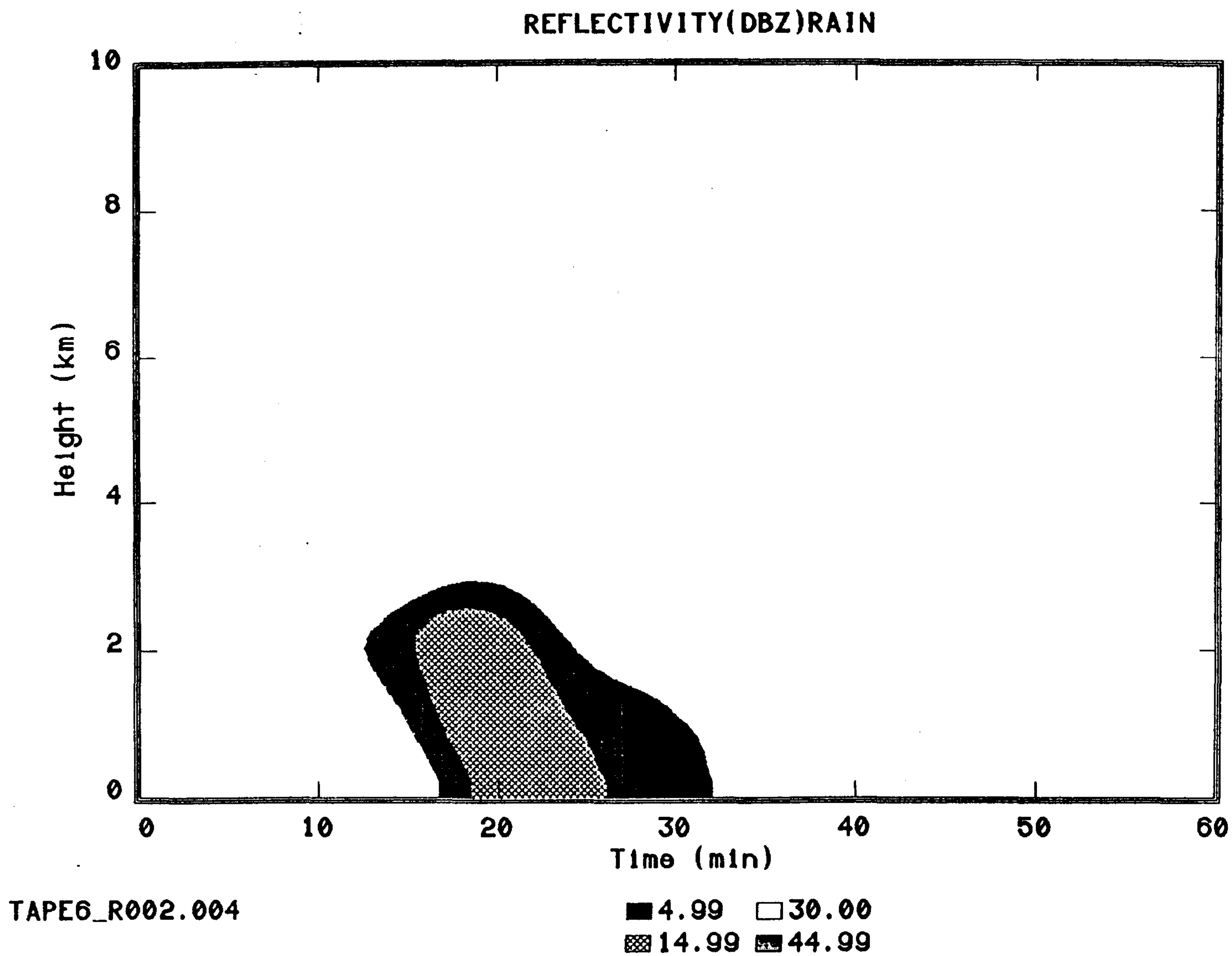
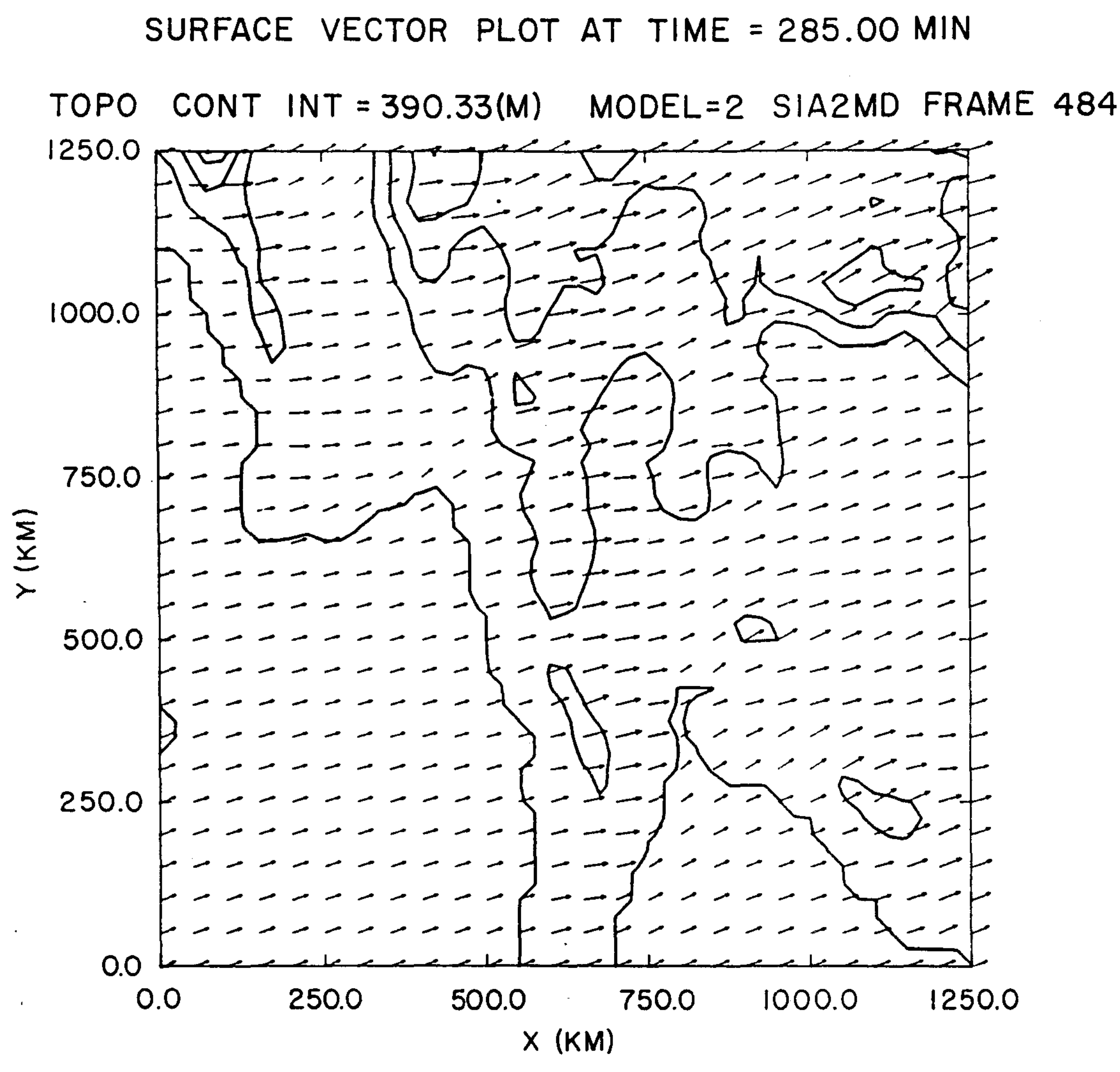
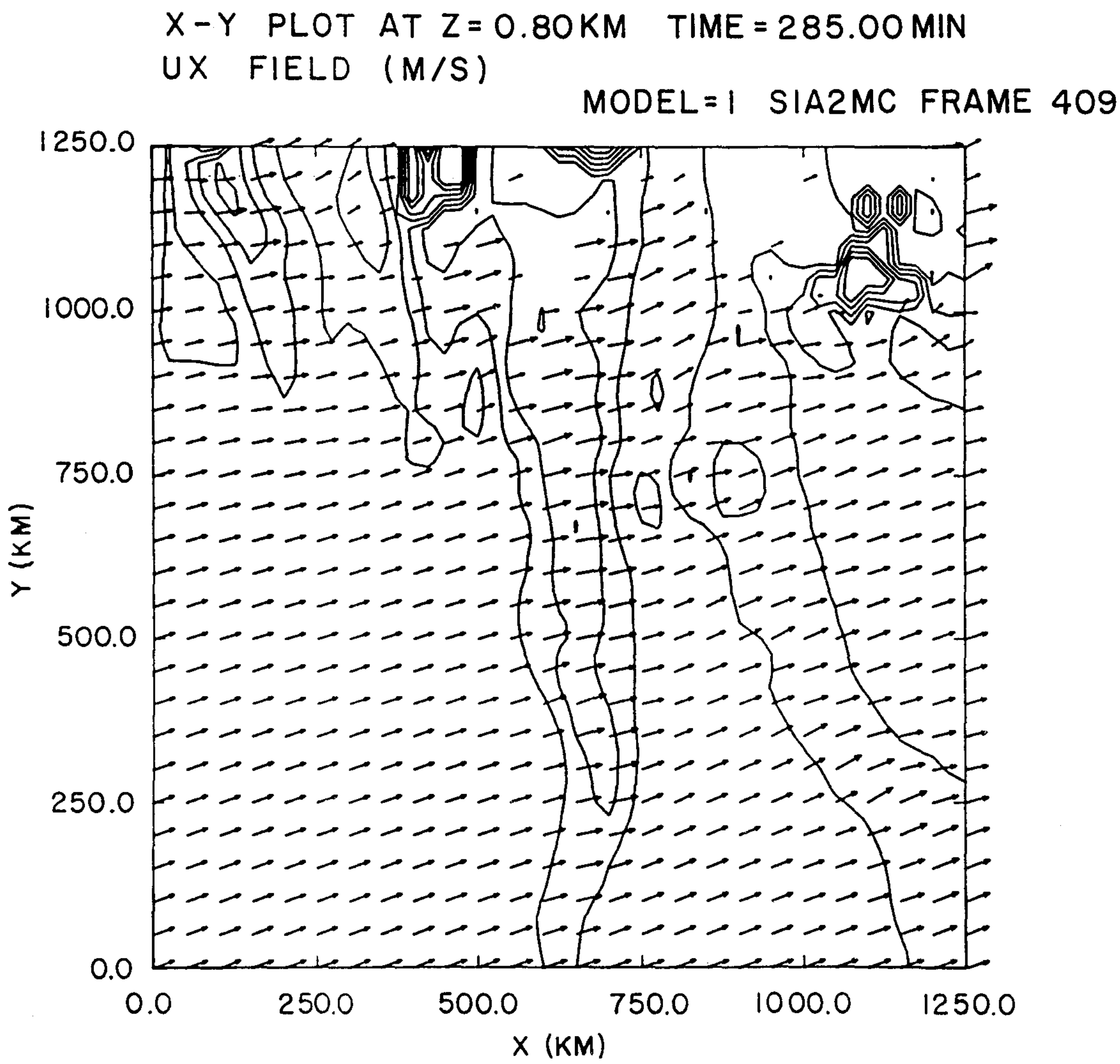


Figure A-8(c). - Same as figure A-7(c) except that particle radius is set at 20 micrometers. - Continued



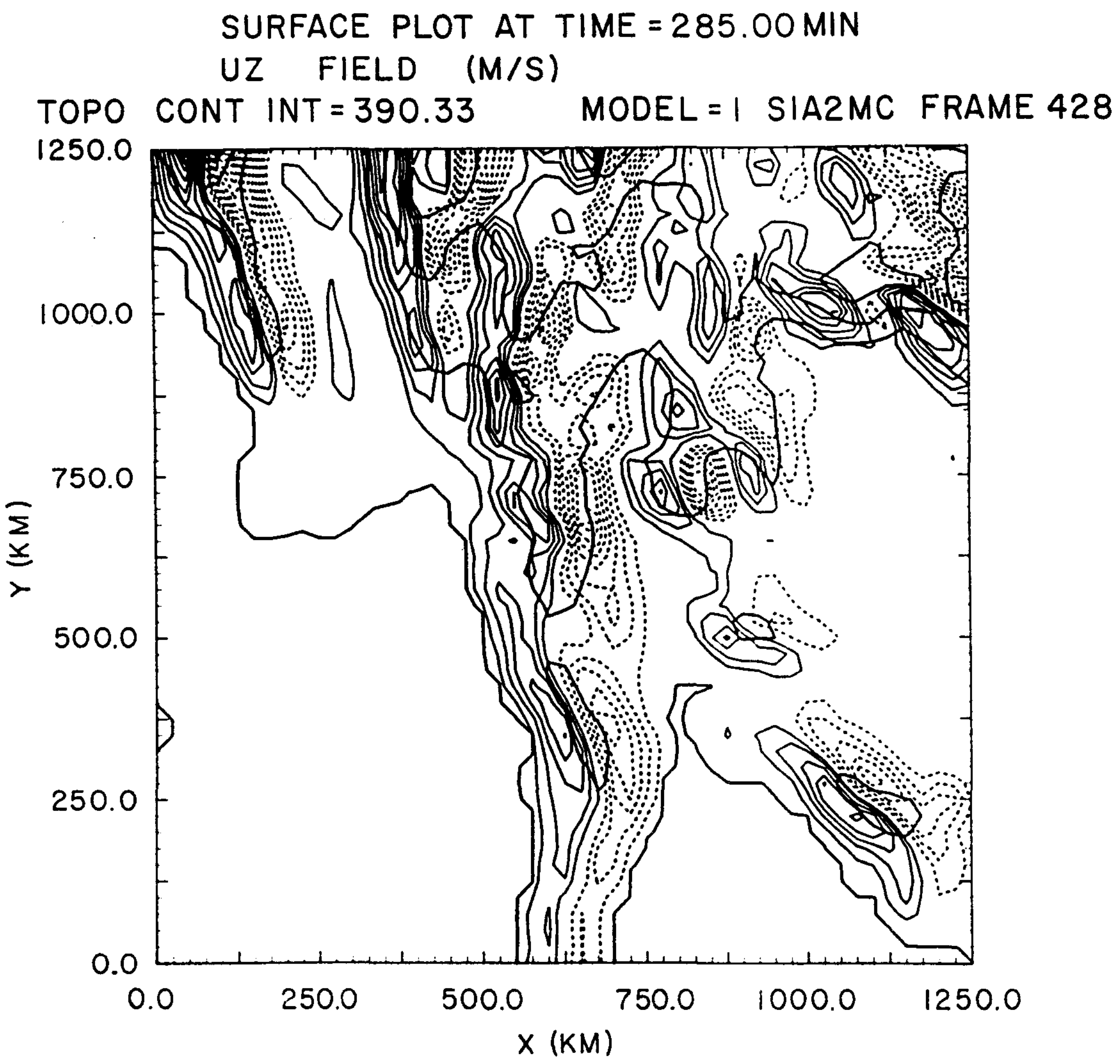
(a) Wind vectors at surface; solid lines are elevation contours at intervals of 390 meters.

Figure A-9. - Wind vectors 285 minutes after initiation of three-dimensional model.



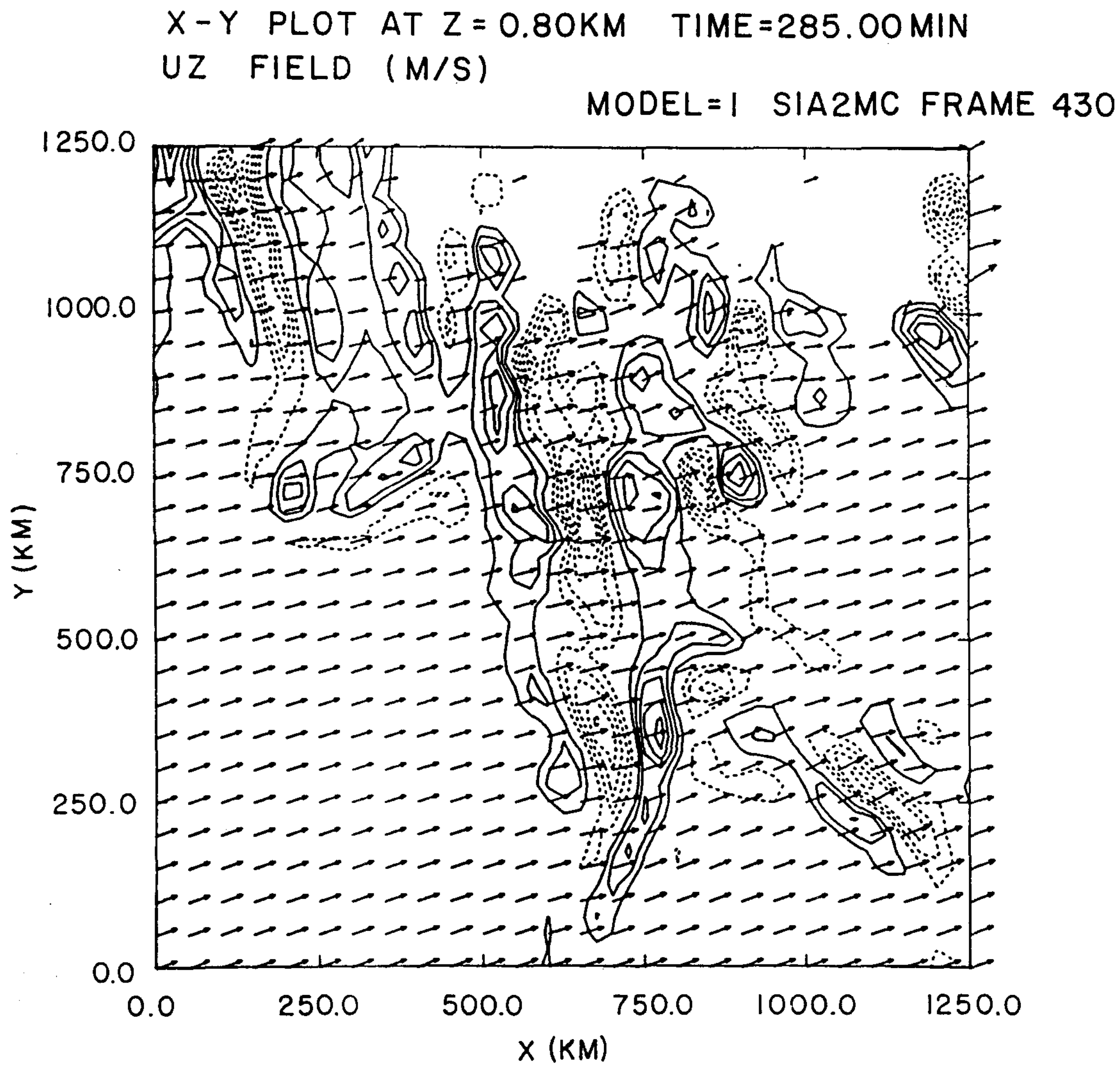
(b) Wind vectors at 800 meters above sea level; solid lines are isopleths of west to east wind component at 2 m s^{-1} intervals.

Figure A-9. - Wind vectors 285 minutes after initiation of three-dimensional model. - Continued



(a) Vertical motions averaged over 800 meters above the terrain. Heavy solid lines show elevation contours at 390-meter intervals; light solid lines show updrafts and dashed lines show downdrafts, both at intervals of 0.0156 m s^{-1}.

Figure A-10. - Vertical motions 285 minutes after model initiation.



(b) Wind vectors and updrafts and downdrafts at 800 meters; isopleths of updraft and downdraft speeds as in (a).

Figure A-10. - Vertical motions 285 minutes after initiation. - Continued

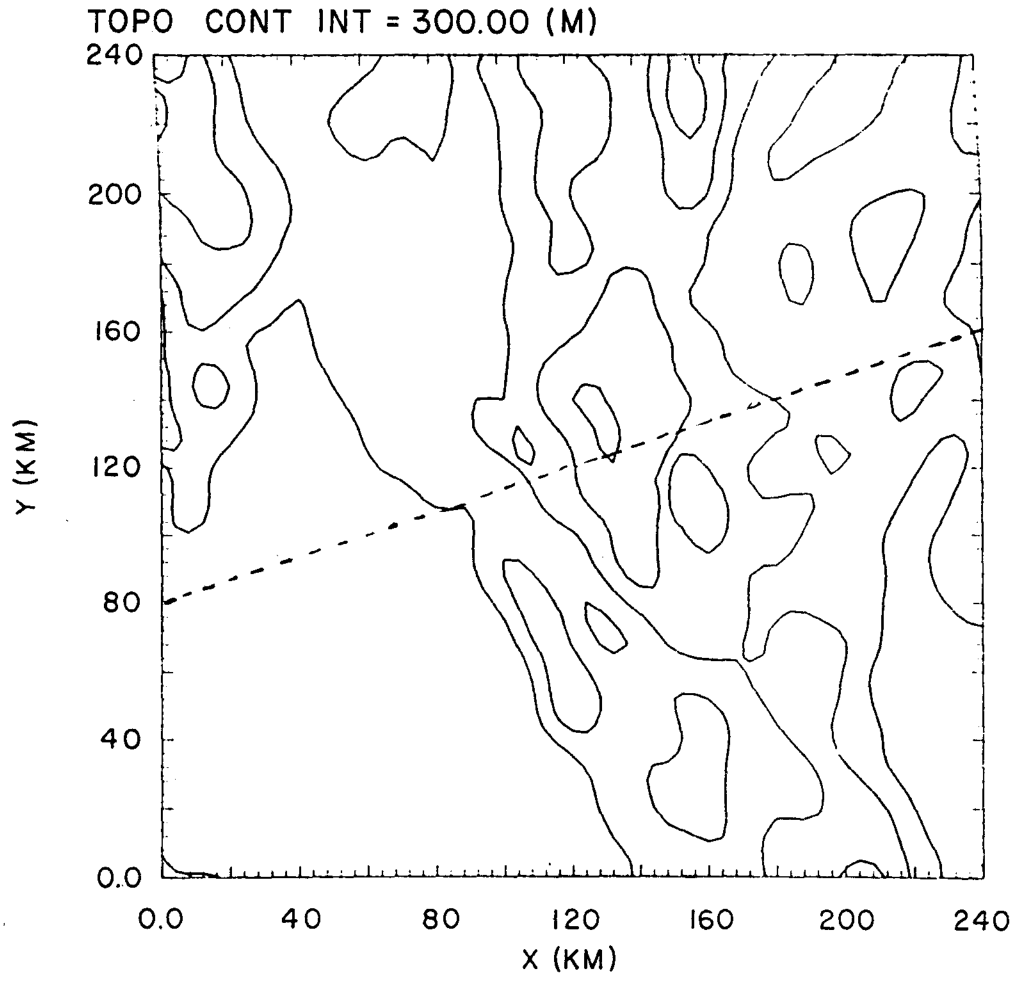


Figure A-11(a). - Topography of area covered in first model of nested grid series. Contour interval is 300 meters. Dashed line indicates vertical cross section used in two-dimensional model runs.

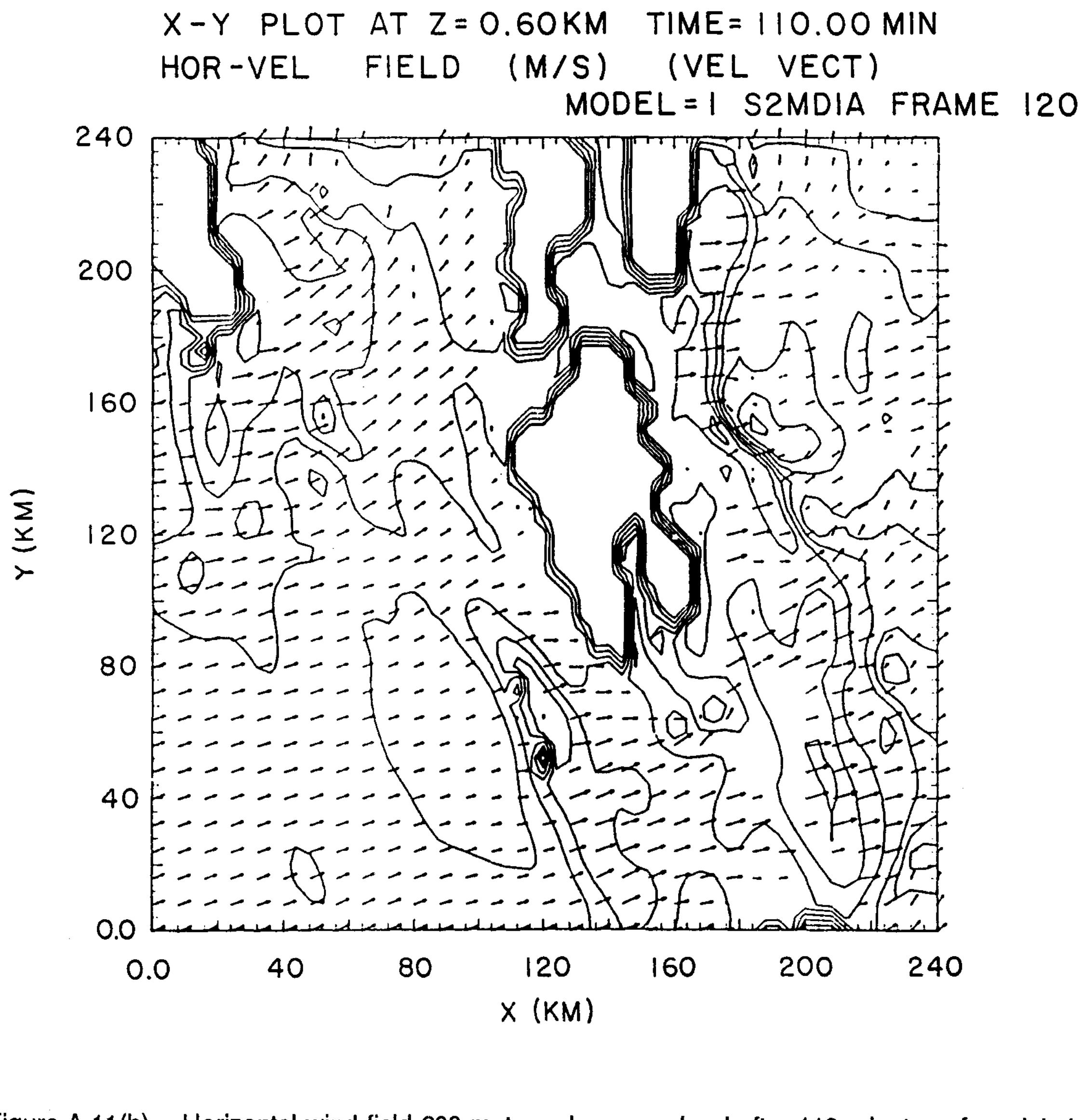
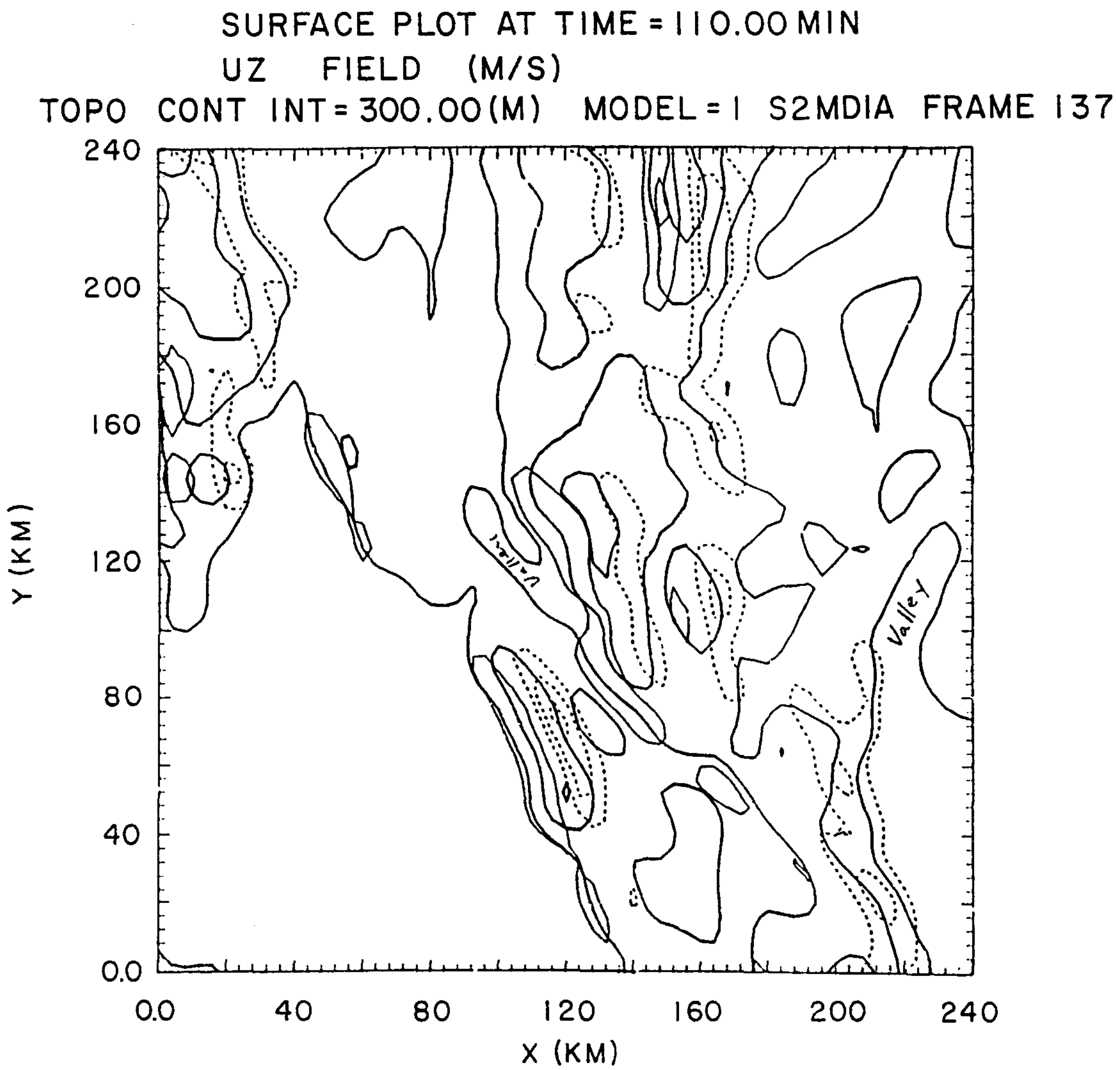
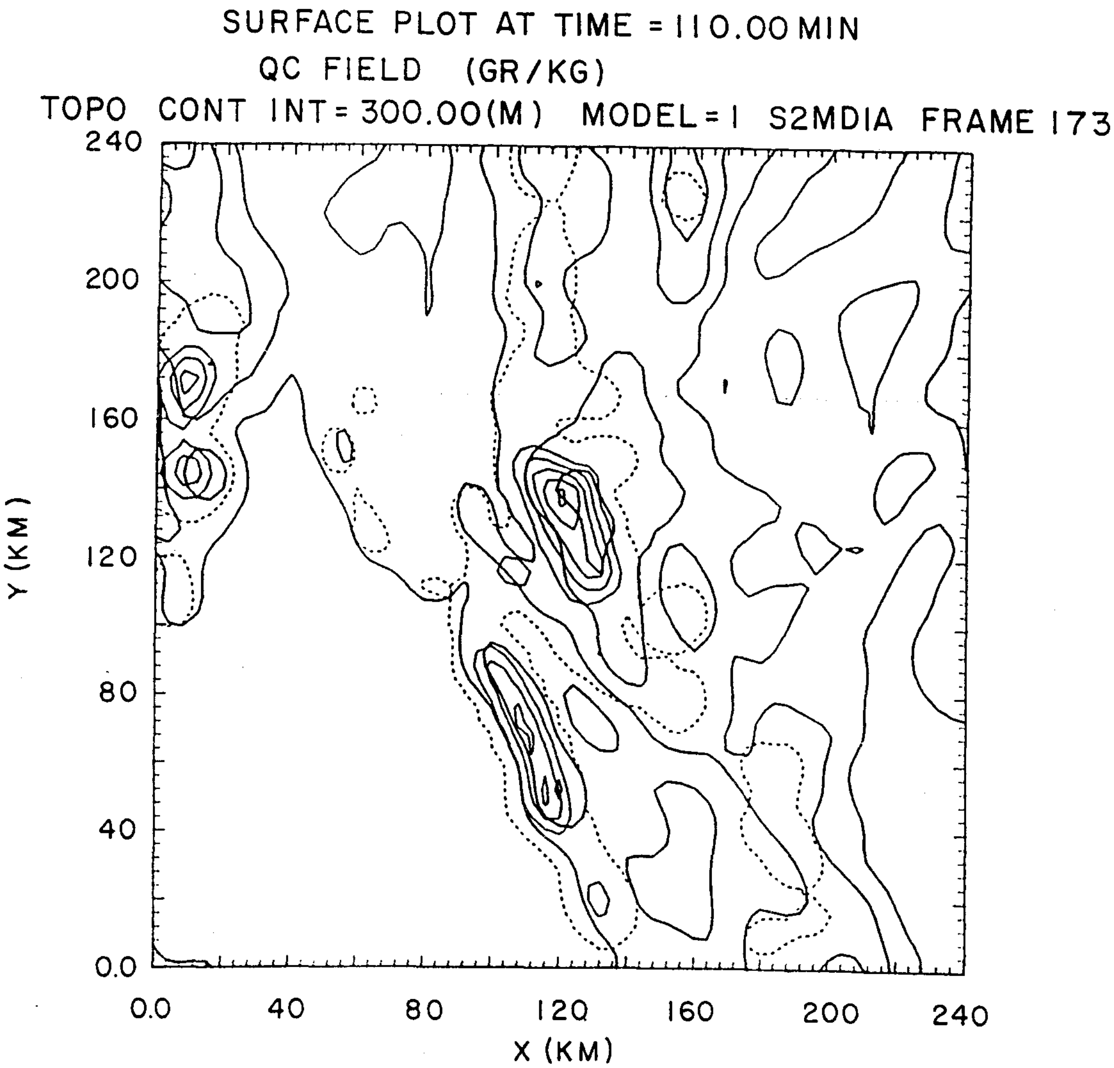


Figure A-11(b). - Horizontal wind field 600 meters above sea level after 110 minutes of model simulation using sounding shown in figure 3 as input. Solid lines are isopleths of windspeed at 2 m s^{-1} intervals.



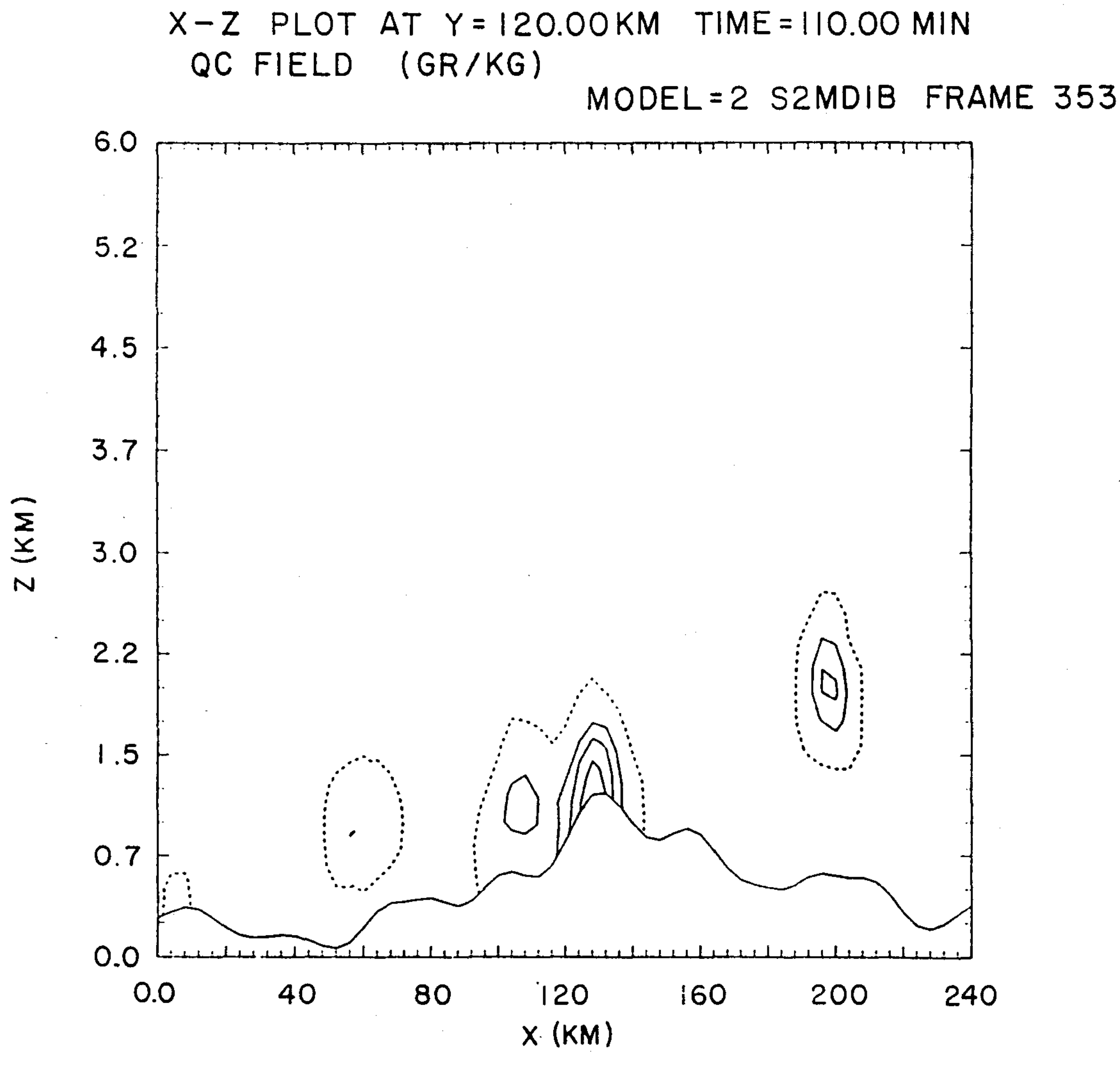
(a) Light solid lines show updrafts and dashed lines show downdrafts, both at intervals of 0.25 m s^{-1}.

Figure A-12. - Vertical wind field and cloud water mixing ratio, both averaged over first 600 meters above the terrain, after 110 minutes of model simulation time using sounding of figure 3 as input. Heavy solid lines show elevation contours at 300-meter intervals.



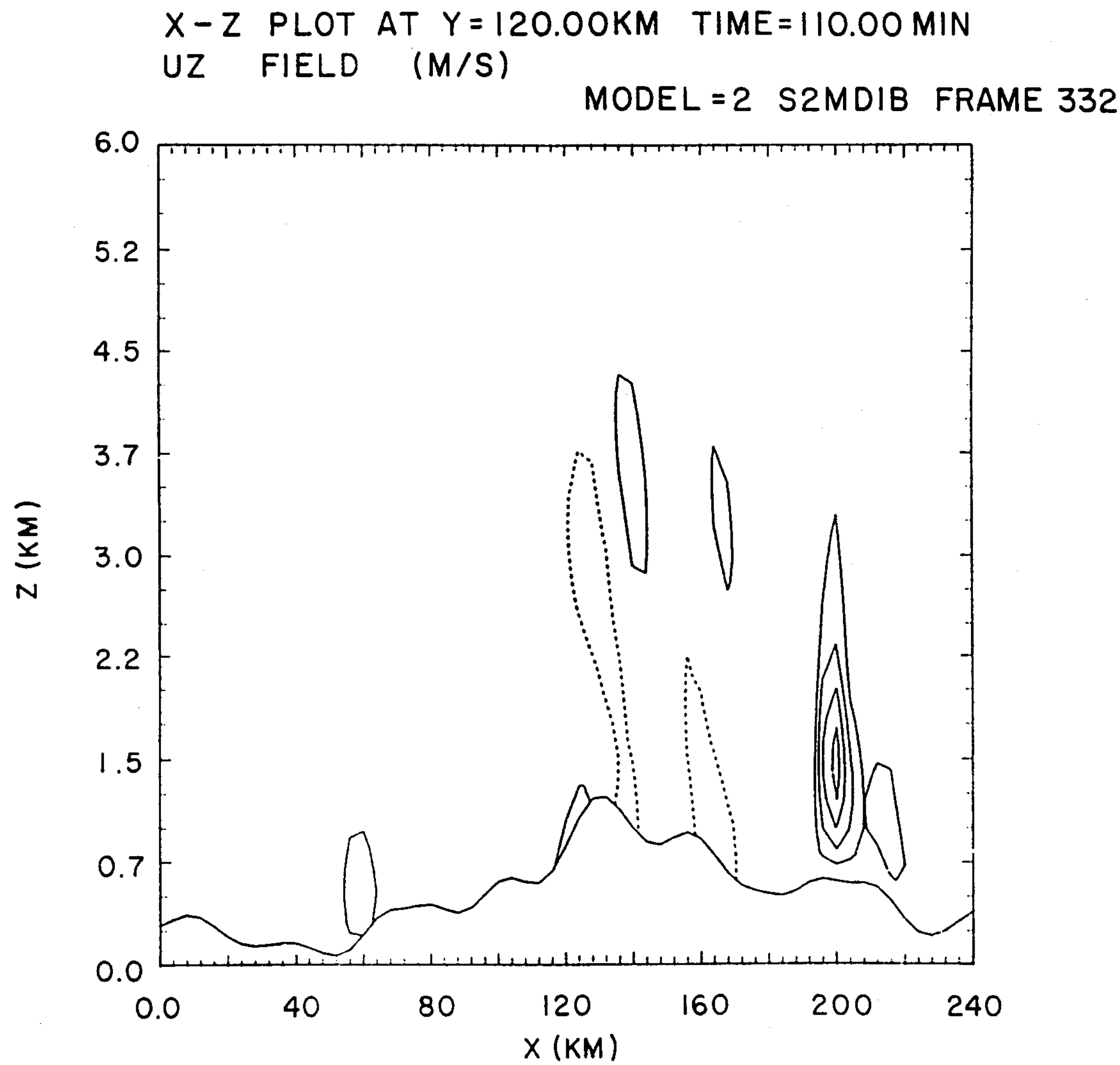
(b) Cloud water mixing ratio. Dotted lines show cloud boundaries; light solid lines show mixing ratio at 0.25 g kg^{-1} intervals.

Figure A-12. - Vertical wind field and cloud water mixing ratio, both averaged over first 600 meters above the terrain, after 110 minutes of model simulation time using sounding of figure 3 as input. Heavy solid lines show elevation contours at 300-meter intervals. - Continued



(a) Dotted lines indicate cloud boundaries; solid lines are isopleths of mixing ratio at intervals of 0.25 g kg^{-1}.

Figure A-13. - Liquid water mixing ratio and vertical velocity in a vertical cross section through model domain of figure A-11.



(b) Solid lines indicate updrafts and dotted lines indicate downdrafts; contour interval is 0.25 m s^{-1}.

Figure A-13. - Liquid water mixing ratio and vertical velocity in a vertical cross section through model domain of figure A-11.

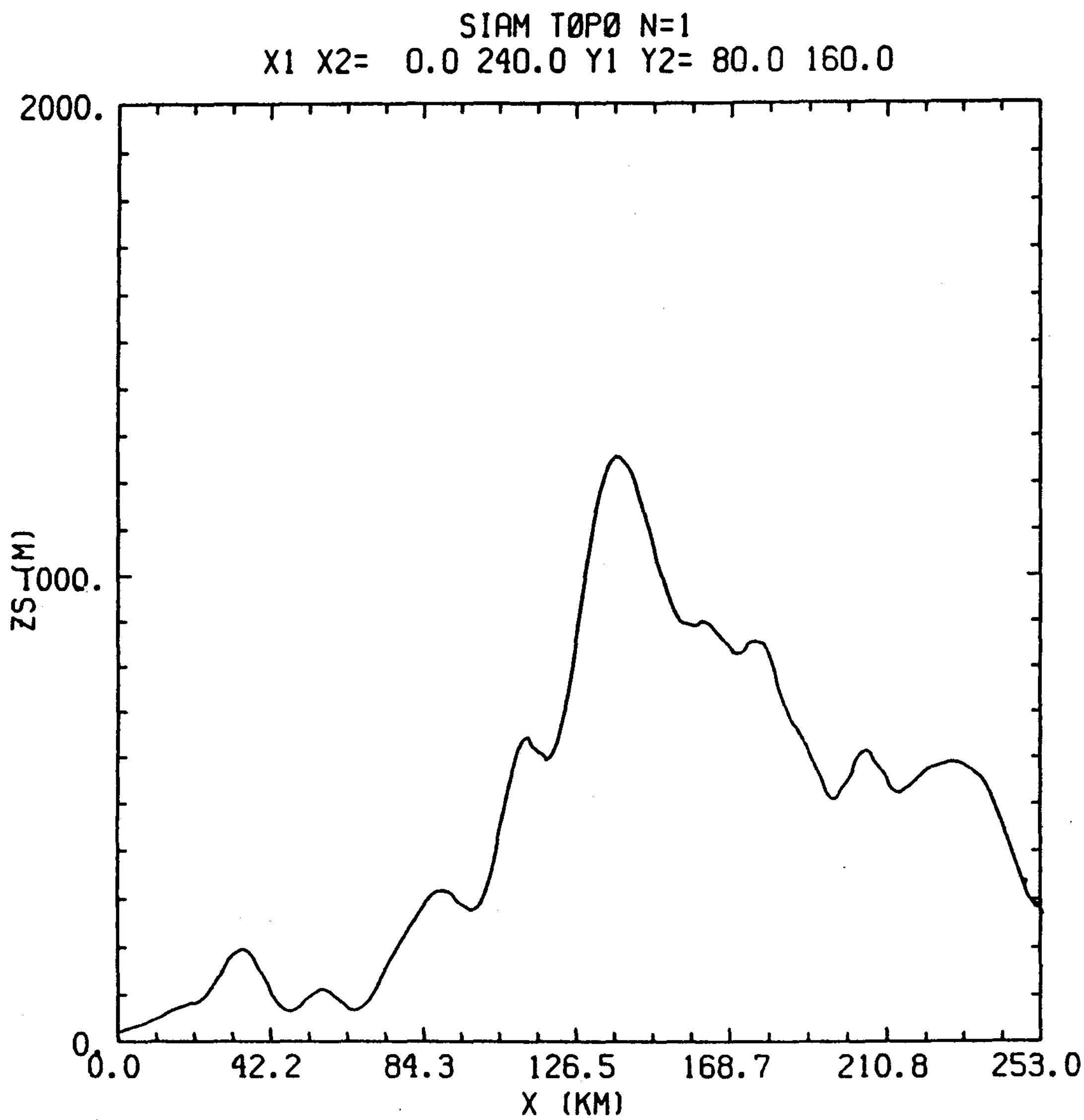
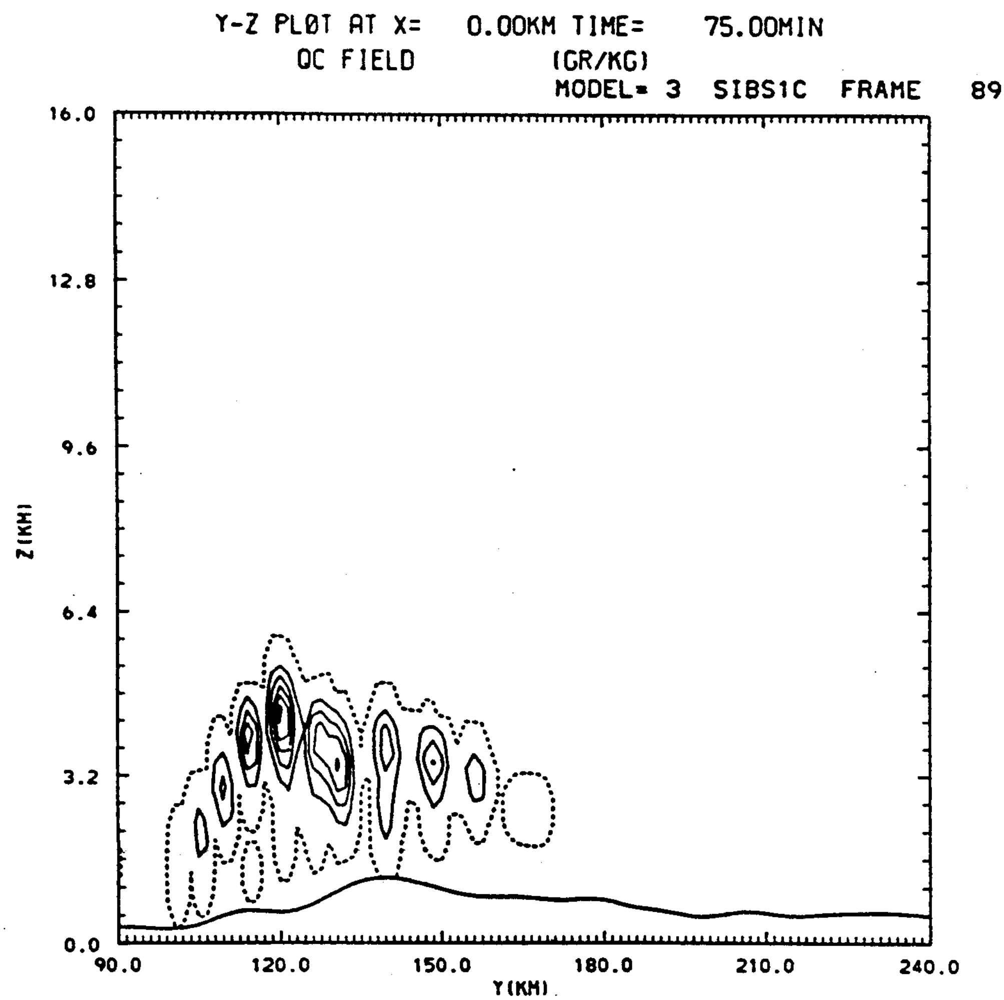
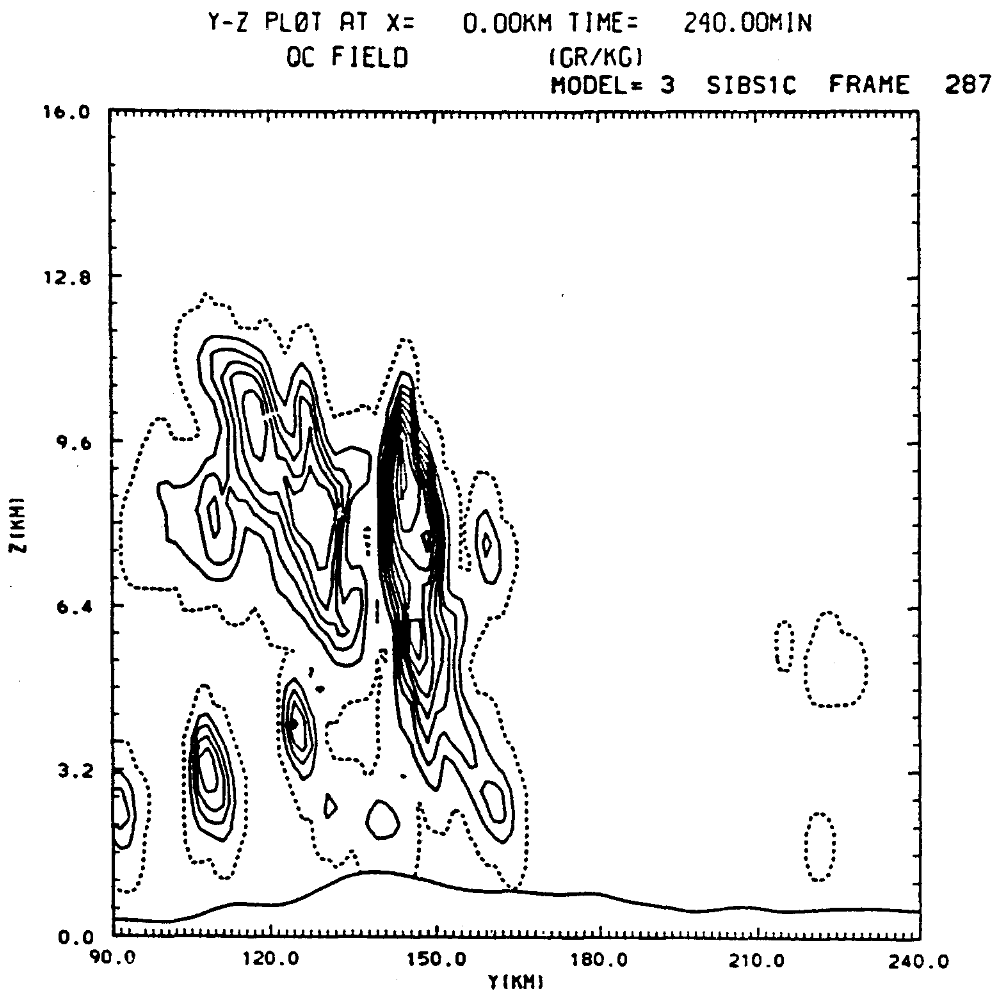


Figure A-14. - Terrain profile for a vertical section of model domain.



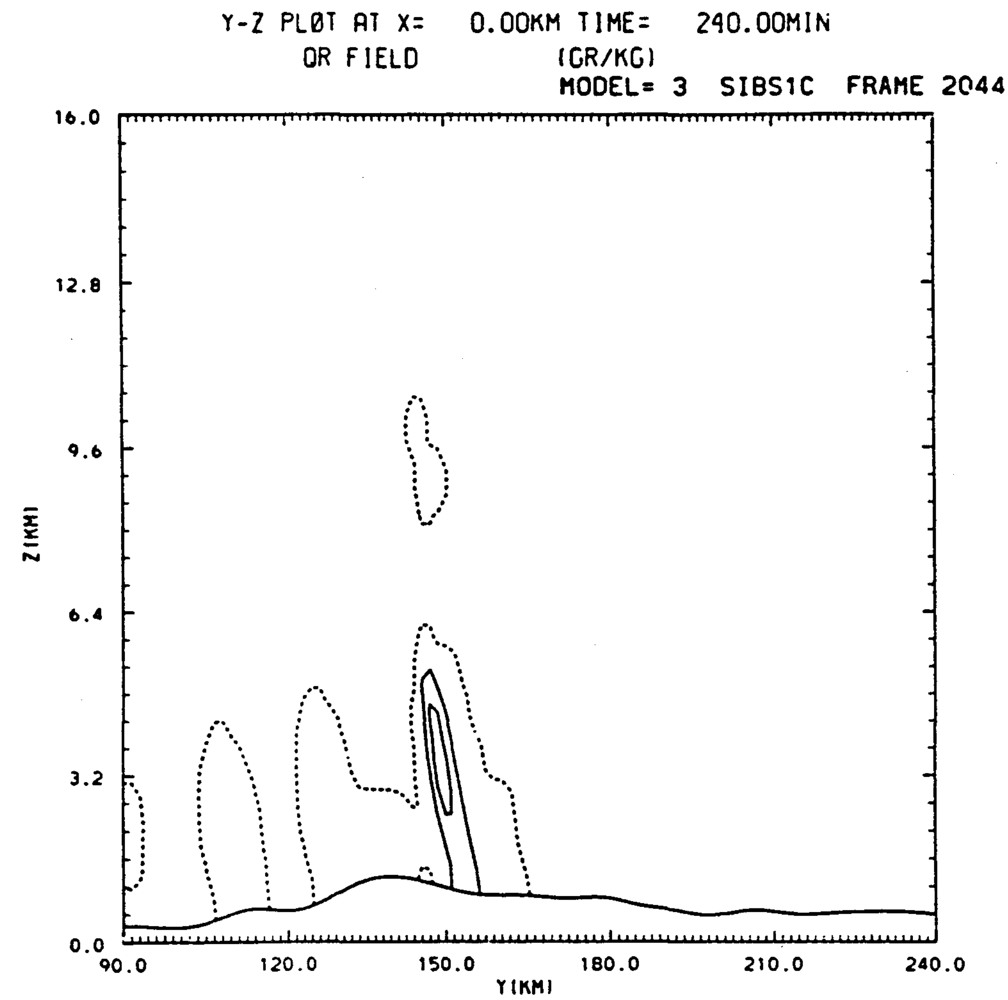
(a) After 75 minutes of simulated time from start of two-dimensional model run.

Figure A-15. - Liquid water mixing ratio in vertical cross section above a portion of line of figure A-14. Dotted lines show cloud boundaries; light solid lines show mixing ratio at 0.25 g kg^{-1} intervals.



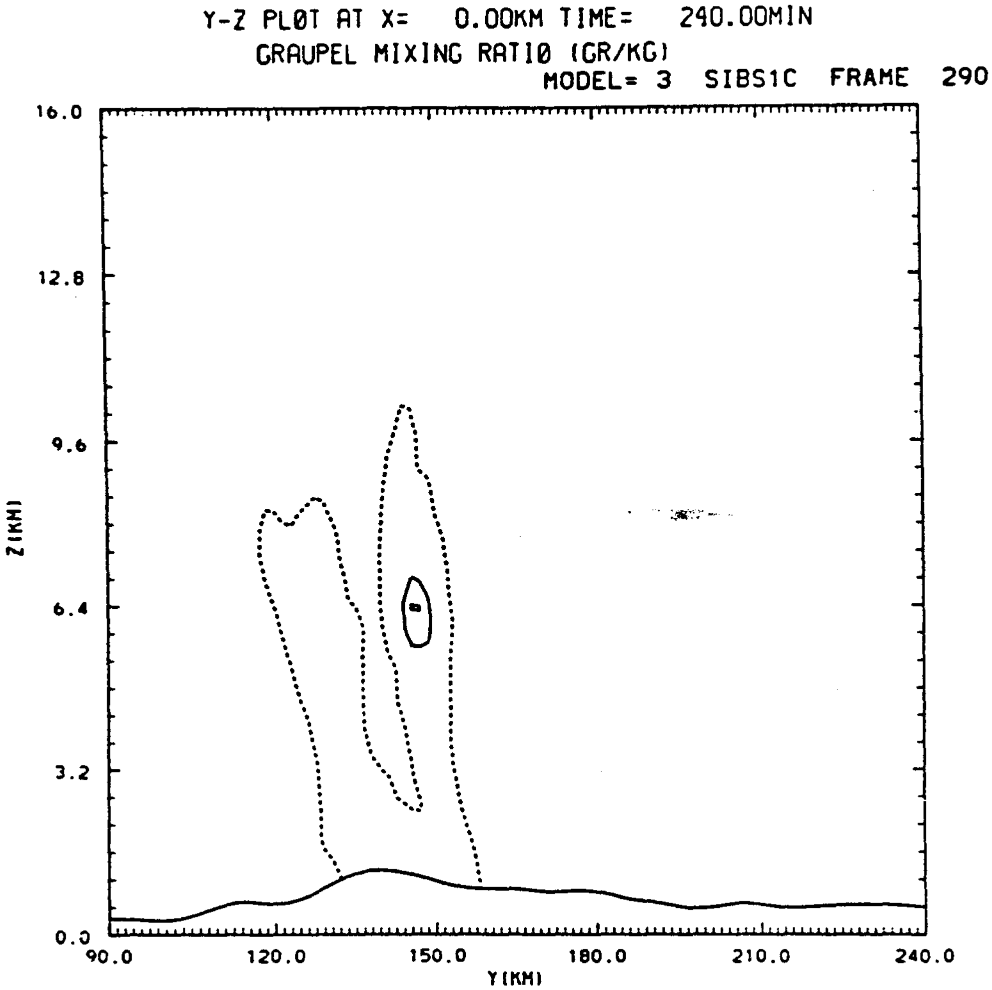
(b) After 240 minutes of simulated time from start of two-dimensional model run.

Figure A-15. - Liquid water mixing ratio in vertical cross section above a portion of line of figure A-14. Dotted lines show cloud boundaries; light solid lines show mixing ratio at 0.25 g kg^{-1} intervals. - Continued



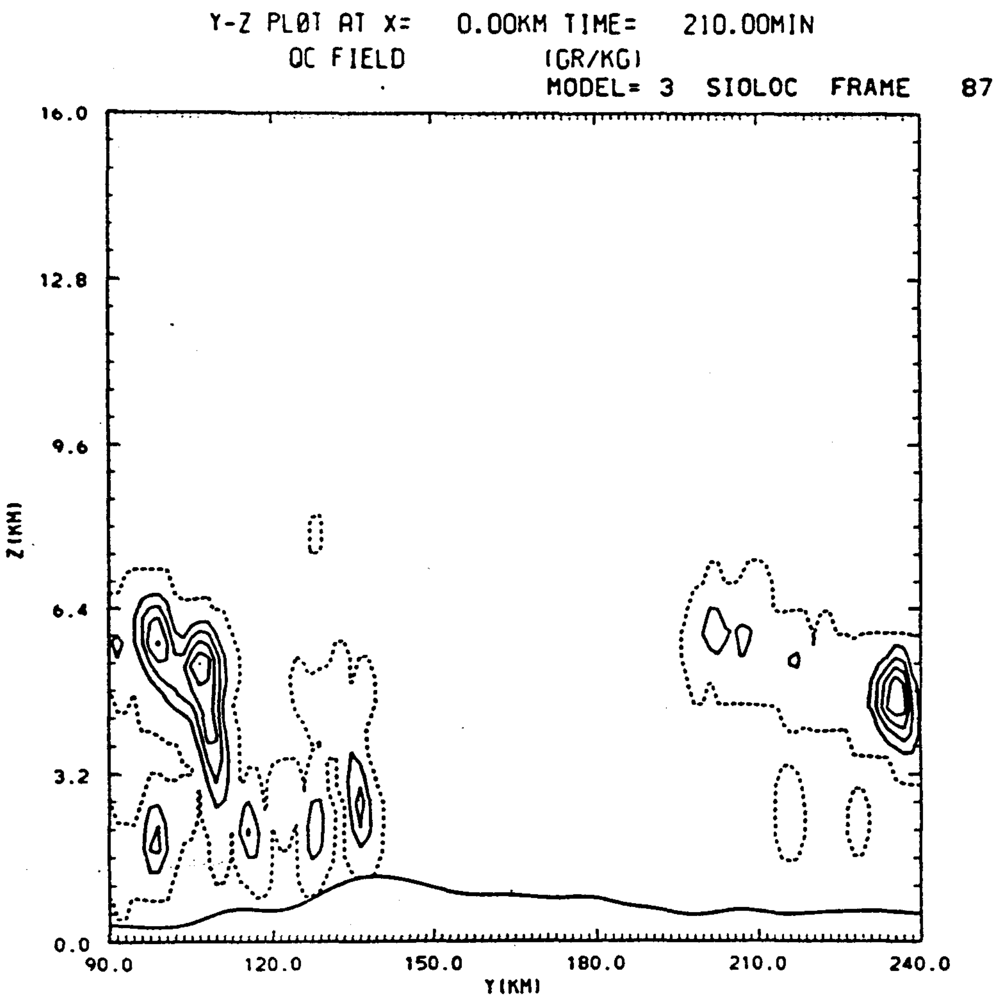
(a) Rainwater

Figure A-16. - Mixing ratios in vertical cross section above a portion of line shown on figure A-14 after 240 minutes of simulated time. Contour interval is 0.5 g kg^{-1}.



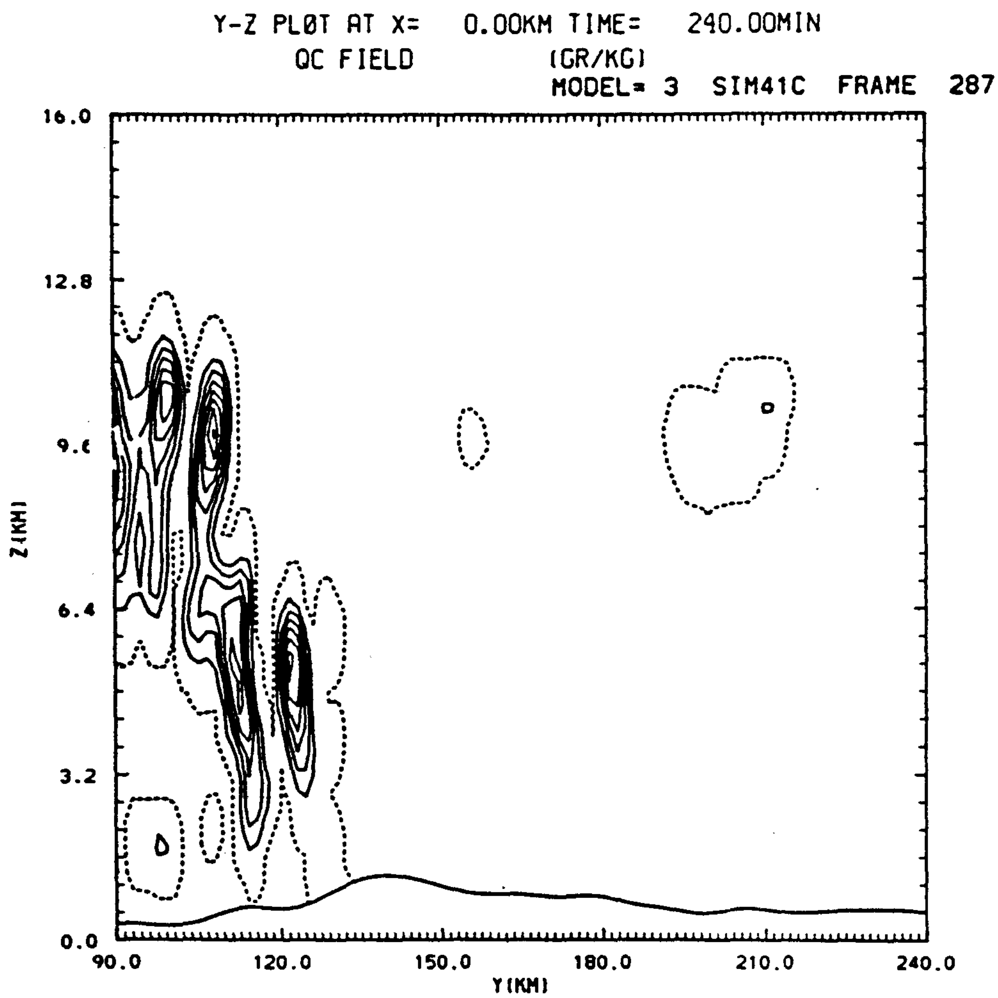
(b) Graupel

Figure A-16. - Mixing ratios in vertical cross section above a portion of line shown on figure A-14 after 240 minutes of simulated time. Contour interval is 0.5 g kg^{-1}. - Continued



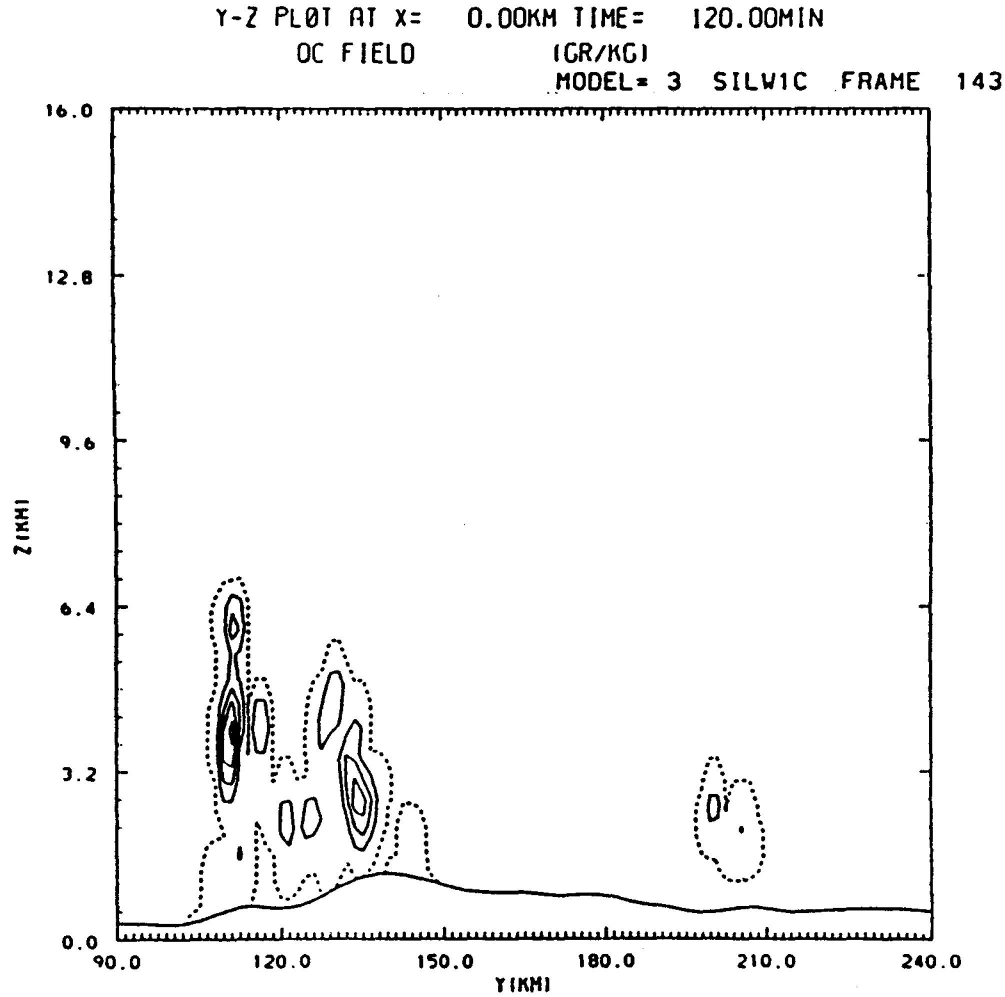
(a) After 210 minutes of simulated time using sounding of figure A-3 as input.

Figure A-17. - Cloud water mixing ratio in vertical cross section above a portion of line shown in figure A-14. Contour interval is 0.5 g kg^{-1}.



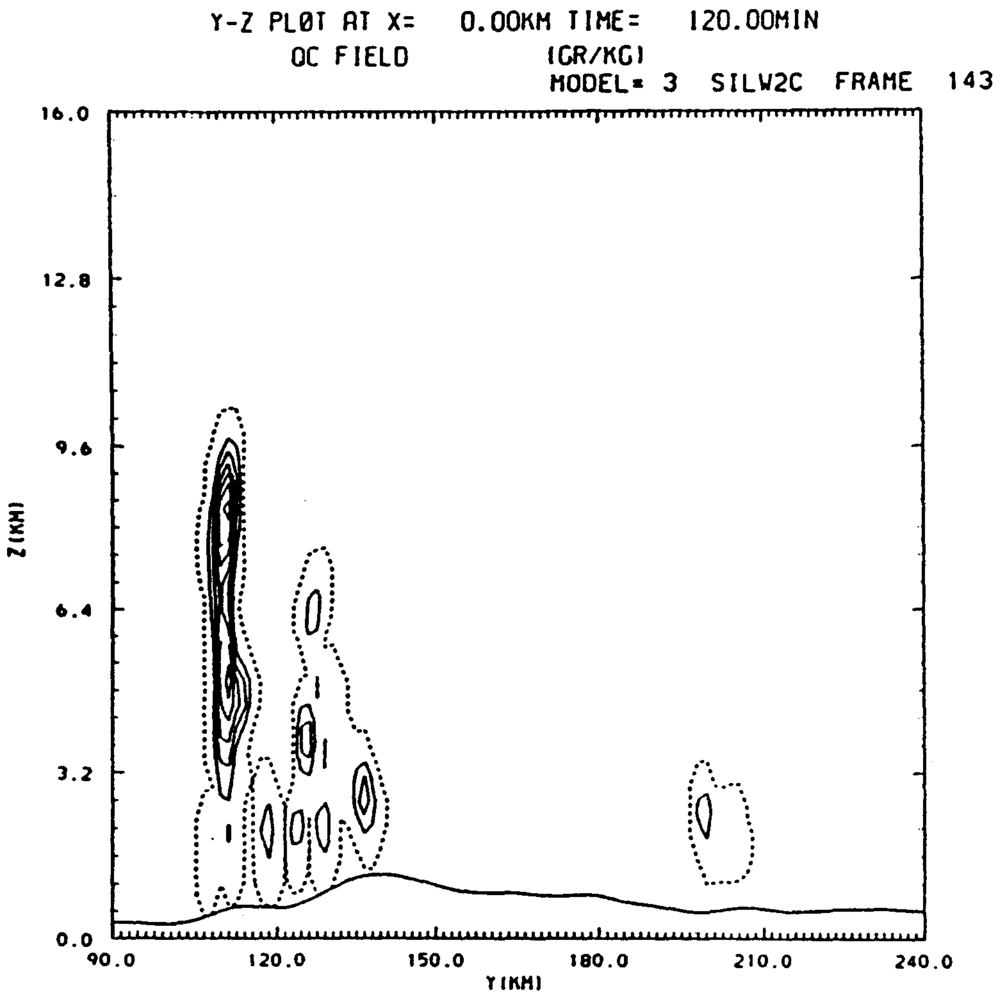
(b) After 240 minutes of simulated time using sounding of figure A-4(e) as input.

Figure A-17. - Cloud water mixing ratio in vertical cross section above a portion of line shown in figure A-14. Contour interval is 0.5 g kg^{-1}. - Continued



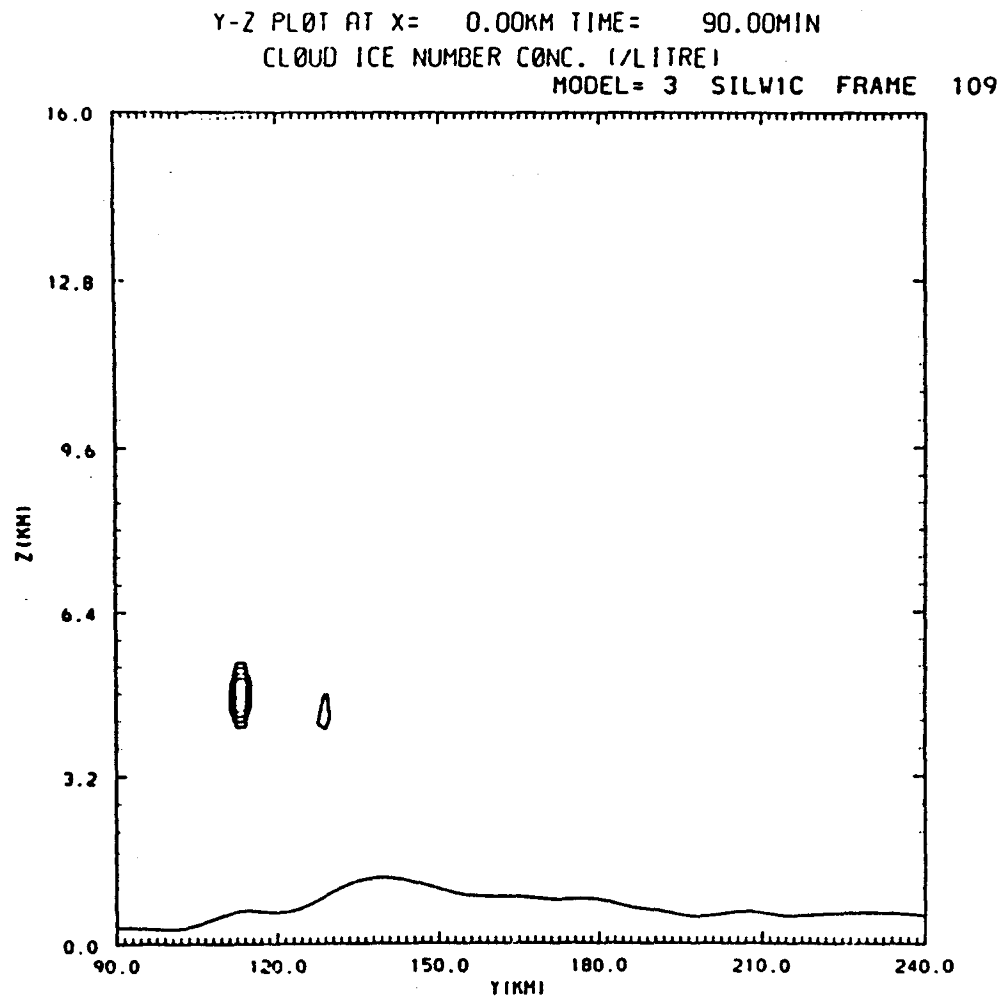
(a) Unseeded

Figure A-18. - Comparison of cloud water mixing ratios in vertical cross section of figure A-17 for unseeded cases at 120 minutes after initialization using sounding of figure A-2(d) as input. This was a case where the wind reversed direction between 3- and 5-kilometer elevation. Contour interval is 0.5 g kg^{-1}.



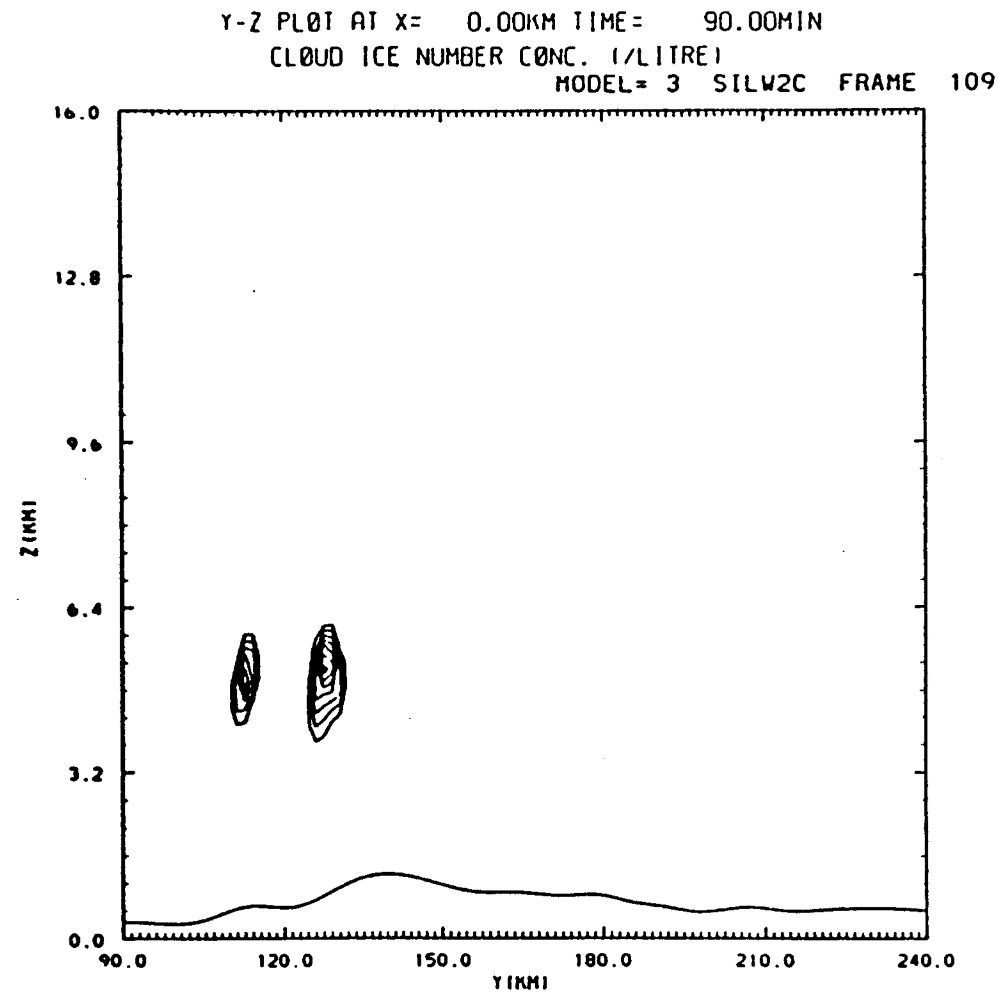
(b) Seeded

Figure A-18. - Comparison of cloud water mixing ratios in vertical cross section of figure A-17 for seeded cases at 120 minutes after initialization using sounding of figure A-2(d) as input. This was a case where the wind reversed direction between 3- and 5-kilometer elevation. Contour interval is 0.5 g kg^{-1}. - Continued



(a) Unseeded, contour interval is $2.3*10^{-7}$ L^{-1}.

Figure A-19. - Ice crystal concentrations in seeded and unseeded cloud cases after 90 minutes simulated time using sounding of figure A-2(d) as input.



(b) Seeded, contour interval is $1.2*10^{-4}$ L^{-1}.

Figure A-19. - Ice crystal concentrations in seeded and unseeded cloud cases after 90 minutes simulated time using sounding of figure A-2(d) as input. - Continued

APPENDIX B

Work plan for hydrometeorological planning studies on characteristics of clouds and precipitation over the target area

APPENDIX B

CONTENTS

TABLES

FIGURES

B.1 PURPOSE

Prior to beginning seeding operations over the demonstration project target area (fig. B-1), preliminary studies using historical satellite imagery, weather observations and rawinsonde, radar, precipitation and hydrological data are required to develop a better understanding of the clouds and precipitation systems that occur there. The historical data should be used to determine if it is possible to differentiate days on which a warm or mixed-phase precipitation process is dominant, and whether this type of information could be used to forecast which will occur during any given time period.

The results of this study will have a direct impact both on the final project design and on the conduct of the seeding operations. It should provide preliminary estimates of the number of potential seeding opportunities within each of the seeding categories and the amount of additional precipitation the seeding operations might produce. It should also lead to the development of techniques, based on real-time utilization of available data, for forecasting seeding opportunities early enough for aircraft with the appropriate seeding material to be on-station on time to properly exploit them.

The scientific studies described in this work plan are only a portion of those required to properly prepare for the demonstration project. Additional scientific studies, some of which will require preliminary field investigations that are needed, will be described in other work plans.

B.2 DATA SOURCES

The studies will require that data sets of reasonably long duration be assembled. A large enough sample should be collected so that it contains examples of below-average, average and above-average precipitation years. Thus, subject to availability, data should be collected for the months of May through October for at least a 10-year period. Data from the most recent historical record is preferred so it best represents current catchment area conditions.

Table B.1 lists the data sets that should be assembled for the planning studies. Data should be obtained in formats that are consistent with existing analysis capabilities. For these studies to begin as soon as possible, the data formats will have to be compatible with hand, rather than computer, processing.

Table B.1. - Data requirements for the planning studies

Data type	Frequency
Satellite imagery	
Visible (GMS)	4 per day
Infrared (GMS)	8 per day
Visible/Infrared (AVHRR)	2 per day
Precipitation	Hourly/daily
Rawinsonde	2 per day
Radar	hourly
Surface and upper air	2 per day (00 and 12 G.m.t. charts)

Table B.1. - Data requirements for the planning studies - Continued

Data type	Frequency
Surface weather station observations	Hourly
Streamflow and reservoir measurements	Hourly/daily

NB: Special data such as those from RRRDI project operations in that area should be included.

B.2.1 Satellite Imagery

Hard copy satellite imagery are available from two different satellites. The Japanese GMS (Geostationary Meteorological Satellite) provides three hourly data with both visible and infrared data during the day and only infrared data at night. Data should be obtained at the maximum resolution possible, that is 1 kilometer for the visible data and 8 kilometers for the infrared. If only degraded visible imagery are available, resolution should not be less than 4 kilometers. An example of a 4-kilometer ion image for Thailand is shown on figure B-2. The infrared imagery should be obtained with a gray-scale enhancement as shown on figure B-3.

Hard copy imagery are also available from the NOAA Polar Orbiter Satellite. This satellite is usually sun-synchronous, passing overhead at 1000 and 2200 local time daily. This satellite provides visible and infrared imagery at 0.5-kilometer resolution.

Source: The most likely source of these data is the Meteorological Department which operates a direct readout satellite ground station in Bangkok. If they do not archive the satellite imagery for long enough periods of time, then it will be necessary to purchase the imagery from the Japanese archive.

B.2.2 Precipitation Data

Precipitation data from all stations within and downstream of the target area should be assembled. A brief list of key stations in the region is given in table B.2. Hourly precipitation data is more desirable than daily totals since hourly data permits direct within-day comparison between precipitation and cloud types and precipitation and streamflow. However, daily totals can be used, especially if they are representative of the total catchment area.

Source: The precipitation data should be available from the Meteorological Department and/or EGAT.

Table B.2. - Key rain gauge sites in or near the project area

Omkoi
Bhumipol Dam
Chiang Mai
Tak
Utteradit

B.2.3 Rawinsonde Data

Twice daily rawinsonde data from Chiang Mai, Bangkok, Rangoon and Port Blair should be obtained. Any special rawinsonde data taken by the RRRDI should be included. The 00 G.m.t. (0700 local time) sounding will, perhaps, be more useful than the 12 G.m.t. (1900 local time) sounding for detailed analysis since the morning sounding will not be modified by convection, and is the first sounding of the day to be used to predict convective activity.

Source: The rawinsonde data should be available from the Meteorological Department, RRRDI and/or Reclamation.

B.2.4 Radar Data

Data from the Chiang Mai radar are, perhaps, the most complete record of radar information for this study. An important addition to these data are those collected by the RRRDI when they conducted seeding operations in this area. Radar summary charts showing echo location, intensity and height every hour would be sufficient for this study. If any of the radars were operated in a volume scan mode, these data would be useful in studying the evolution of echo development.

Source: The radar data should be available from the Meteorological Department and the RRRDI.

B.2.5 Surface and Upper Air Data

Surface and upper air charts for 850, 700, 500, 300, and 200 mb should be obtained for both 00 and 12 G.m.t. Hourly surface weather observations should be obtained as well. These data should be used to classify the large-scale synoptic controls over convective development. Used in combination with the satellite imagery the data should also be used to identify mesoscale features that are associated with or influence the convective activity.

Source: The various weather data should be available from the Meteorological Department.

B.2.6 Hydrologic Data

Data from all the streamflow gauges in the target area and Bhumipol Reservoir inflow, outflow, and water level should be obtained. Here again, hourly data, if available, are preferable to daily data; however, daily data can be used.

Source: The hydrologic data should be available from EGAT.

B.3 METHODS AND PROCEDURES FOR DATA ANALYSIS

Each of the above data sets should be first analyzed independently and then these analyses should be combined to arrive at an overall understanding of the meteorological processes controlling convective cloud development, precipitation, and streamflow in the demonstration project area. Examples of methods and procedures for analyses similar to that proposed for the AARRP are given in the Bureau of Reclamation report to the Tennessee Valley Authority entitled, "Potential Opportunities for Precipitation Augmentation in the Eastern Tennessee Valley" by Reynolds et al. (1988).

B.3.1 Satellite Imagery Analysis

The visible satellite imagery should be analyzed to identify the prevailing cloud types and the mesosynoptic forcing mechanism that might have induced each cloud type. The type of imagery available will determine the temporal resolution for this study. If possible, the results of this analysis should be recorded in 6-hour time blocks: 00-06, 06-12, 12-18, and 18-00 G.m.t. An example of a worksheet that could be used to record the data is shown on figure B-4. Some additions/deletions to the list in figure B-4 to account for the dominant convective processes that occur in Thailand will likely be necessary.

Cloud top temperature will be an important parameter in this study in that it will help determine whether convective clouds have penetrated the freezing level. The infrared satellite imagery with a gray-scale enhancement curve should be analyzed for cloud top temperature.

Results of these studies should be tabulated by month and by season in terms of the number of 6-hour periods each cloud type and mesosynoptic scale mechanism was observed. The proportion of clouds in each 6-hour period as a function of cloud top temperature should also be tabulated.

It is very useful when analyzing the satellite imagery to simultaneously look at the surface and upper level synoptic charts. This will aid in the identification of a relationship between the synoptic scale flow and cloud organization and structure, and between the strength of the convection and the mesosynoptic scale forcing mechanism. It will help identify what factors inhibit cloud growth above the freezing level. It will also aid in the stratification of the synoptic/mesoscale features that occur each day.

Another aid in interpreting the satellite imagery are the hourly surface weather observations. If a high thin overcast blocks the satellite's view from space, the hourly surface observations may provide guidance as to the existence and nature of the underlying clouds.

B.3.2 Rain Gauge Data Analysis

The hourly and daily rain gauge data should be analyzed in several ways:

a. Monthly and seasonal rainfall totals should be tabulated and compared to the long-term climatic average to determine the degree of wetness/dryness of each month and season.

b. The distribution of the daily precipitation amounts should be constructed and then compared to the degree of wetness/dryness for each month to see if it is the number of precipitation days or a few very wet days that contribute to the totals.

c. The number of rain days per month and the timing of the rainfall during the day should be examined to determine if there is any diurnal variation in the rainfall.

d. The precipitation data for the below-average, average, and above-average rainy seasons should be compared in terms of the number of convective days, strength of convection, and organization of the convection on a daily, monthly and seasonal basis.

f. The means of hourly, 3-hourly, daily, and monthly precipitation data should be calculated along with their statistical variances to establish the precipitation evaluation baseline for the randomized seeding project.

The above rainfall characteristics should be tabulated separately for each of the particular regions of interest within the study area. This might include the area upwind of the target area, the target area, the near-downwind area (within 20 km) and the far-downwind area (20 to 100 km). This will allow determination of the effects of orography on the precipitation patterns and the occurrence of rain cloud redevelopment downwind of the target area.

The hourly and daily precipitation totals should then be compared to the satellite cloud study results. Specifically the relationship between convective strength, as measured by cloud organization and cloud top temperature, and rainfall amount can be determined. Weakly organized and shallow convective clouds that do not penetrate the freezing level might exhibit a different precipitation intensity than do the strongly organized, taller convective systems. By quantifying precipitation amount with each cloud type, the percentage contribution of each cloud type to the seasonal precipitation can be estimated. The precipitation analysis combined with the satellite study results should help with the estimation of the frequency of occurrence of warm and mixed-phase precipitation events over the area.

B.3.3 Rawinsonde Data Analysis

The rawinsonde data will provide information on atmospheric stability and mean wind flow, which are important in determining the nature of convective development and, therefore, the likely precipitation process that might be dominant. The following standard stability indices should be calculated from each atmospheric sounding: the Showalter Index, the Lifted Index, the Total-Totals Index and the K-Index. Two other stability-related parameters (indices) should also be calculated: the difference between the pseudoadiabatic temperature through cloud base and the environmental temperature at 500 mb, and the available potential energy of a cloud base air parcel as measured by the area between the parcel moist adiabat and the environmental lapse rate. These indices should be calculated from the 00Z sounding and then compared to the subsequent cloud development to determine their value as predictor variables.

One of the outcomes of this particular study should be to determine the representativeness of the various sounding sites to the project area. In particular, does the sounding from one site better predict convective cloud development than the others?

B.3.4 Radar Data Analysis

The hourly radar summary maps should be used to tabulate the following information:

- Number of hours of echo each day including their start and stop times, and the height of their first echo.
- Number of echo days per month.
- Maximum echo height and intensity.
- Echo motion.

If possible these radar statistics should be tabulated separately for the target area and the downwind area. These results should then be compared with the satellite and rainfall analysis results to verify that they give consistent indications and to further refine the general findings.

B.3.5 Hydrologic Data Analysis

The daily and, if available, hourly streamflow and reservoir data should be analyzed for the following purposes:

a. The means and variances of the data should be calculated to establish the hydrologic evaluation baseline for the randomized seeding project.

b. The streamflow and reservoir data should be compared to the precipitation data to determine how long it takes for a precipitation event to show up in the hydrographs.

c. Comparison of the hydrologic and precipitation data should also be made in an attempt to estimate how much of the rain actually runs off as streamflow as functions of time of the year and relevant basin conditions. EGAT'S hydrologic basin model is, perhaps, the best way to make this estimate.

It is quite possible that the above information is already available from EGAT. Therefore, EGAT should be consulted before starting these analyses. The information obtained from EGAT should be supplemented only as necessary to complete the analyses.

B.4 SUMMARY

This work plan has been written to guide studies that will begin to provide an understanding of the meteorological and hydrological conditions in the target area of the AARRP demonstration seeding project. The study results will help provide a more quantitative estimate of the likely number of seeding candidates in each of the precipitation categories in both dry and wet years. It should also aid in the development of procedures for forecasting the occurrence of the seeding candidates. Additional scientific analyses and preliminary field investigations that further contribute to these objectives will be the subject of future work plans.

B.5 REQUIRED ACTIONS

A team of RRRDI scientists should be assigned to implement the studies outlined in this work plan. These scientists should be selected from among those who will be or are already designated to be part of the AARRP Analysis/Evaluation Group. A team leader should be appointed to coordinate these and subsequent hydrometeorological planning studies. When these studies are completed, these AARRP analysis/evaluation scientists will be in a better position to successfully conduct the analysis/evaluation studies associated with the demonstration project itself.

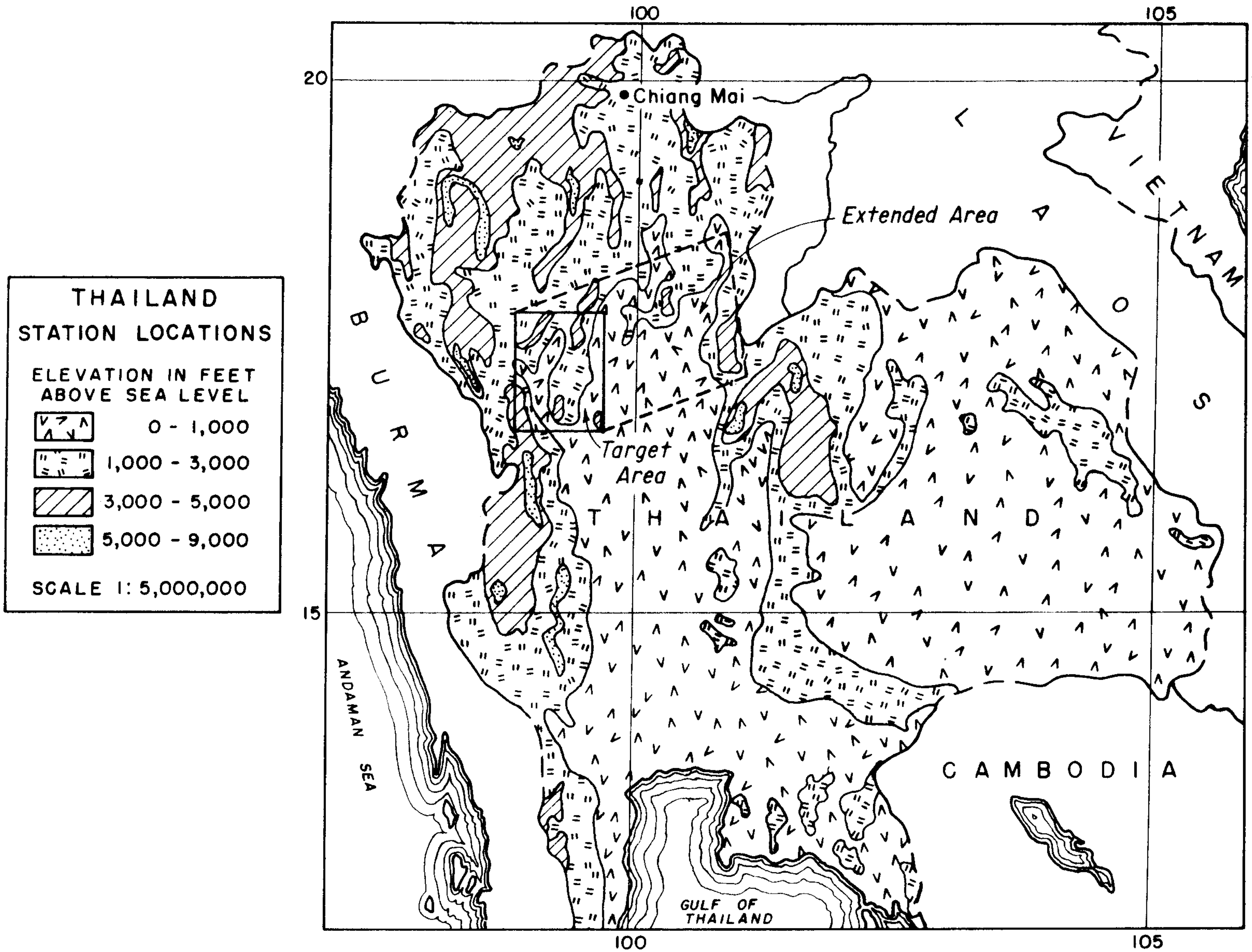


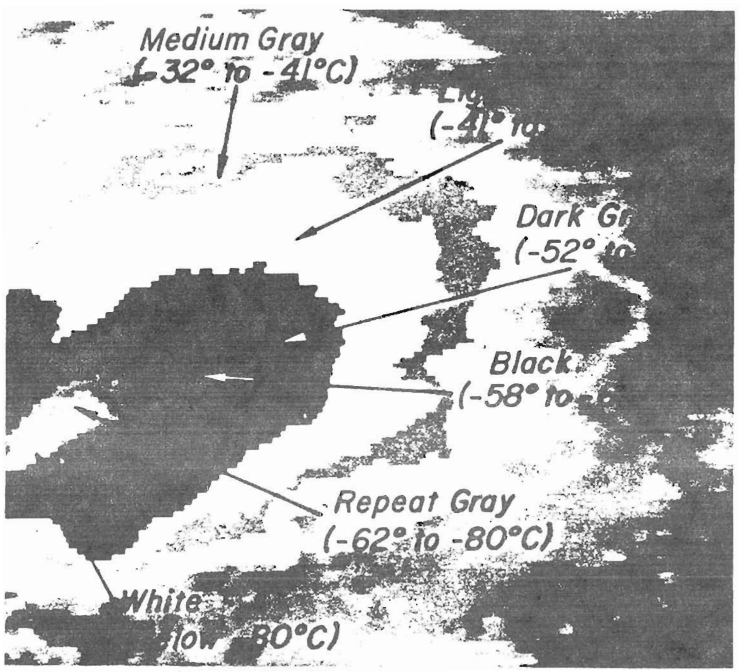
Figure B-1. - Map of demonstration project area.

Figure B-2. - Example of a 4-kilometer resolution image for Thailand.

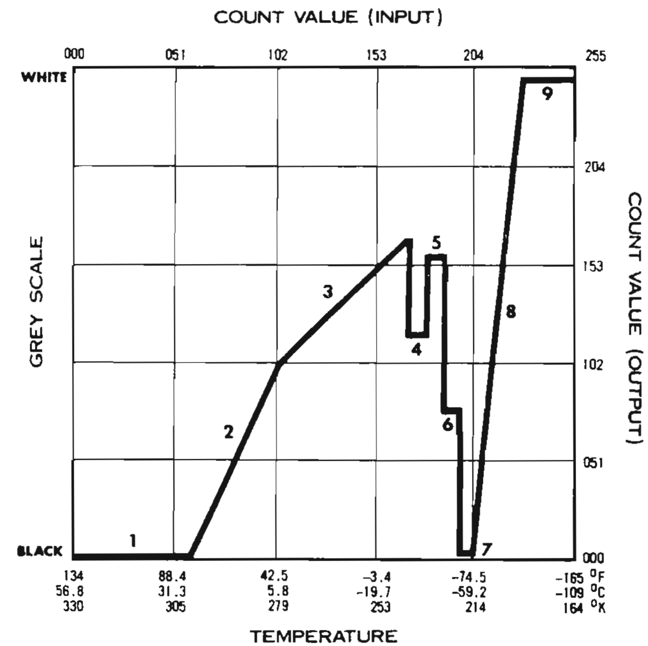
ENHANCEMENT MB

GENERAL DESCRIPTION

Segments 1, 2, and 3 are extracted directly from the old Z curve: This steeper slope will give better definition to the low and mid clouds. Segments 4 through 7 contours convective areas. Segment 8 slopes with a factor greater than zero from -63° C to -80° C which allows for good definitions of very cold domes. Although specific temperatures cannot be obtained--it better isolates the coldest tops by gradually going to white rather than producing a complete white-out at all temperatures colder than -65° C. This curve is utilized for rainfall estimates.



ENHANCEMENT MB



SEGMENT NUMBER	°C TEMPERATURE	COMMENTS	
1	58.8 to 29.3	Little or no useful Met Data	(Black)
2	28.8 to 6.8	Low Level/Sea Surface Difference	
3	6.3 to -31.2	Middle Level - No Enhancement	
4	-32.2 to -42.2	First Level Contour	(Med Gray)
5	-43.2 to -53.2		(Light Gray)
6	-54.2 to -59.2	Thunderstorm	(Dark Gray)
7	-60.2 to -63.2	Enhancement	(Black)
8	-64.2 to -80.2	Overshooting Tops Enhancement	
9	-81.2 to -110.2		(White)

Figure B-3. - Gray-scale enhancement curve used on many infrared satellite images.

Day	1				2				3				etc
Time Period	1	2	3	4	1	2	3	4	1	2	3	4	
<u>Cloud Types</u>													
Clear													
Convective Cells													
Convective Band													
Deep Stratiform													
Embedded Bands													
Convective Complex													
Cumulonimbus													
Cirrus													
Shallow Stratus													
Other													
<u>Synoptic/Mesoscale Features</u>													
Upper Cut-Off													
Cold Front													
Deformation													
Comma Cloud													
Overrunning													
Gust Front													
ITCZ													
Other													

Time Periods

1 0000Z-0600Z
2 0600Z-1200Z
3 1200Z-1800Z
4 1800Z-2400Z

Figure B-4. - Sample worksheet for tabulating the results of the satellite imagery analysis.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.