Numerical Simulations of Snowpack Augmentation for Drought Mitigation Studies in the Colorado Rocky Mountains

Final Report

Submitted to
U.S. Bureau of Reclamation
Weather Damage Modification Program
Denver Federal Center
Denver, Colorado 80225

In Fulfillment of
Financial Assistance Agreement No. 03-FC-81-0925

September 2005

Department of Natural Resources
Colorado Water Conservation Board
Flood Protection & Weather Modification Permitting
Denver, Colorado 80203

Numerical Simulations of Snowpack Augmentation for Drought Mitigation Studies in the Colorado Rocky Mountains

Final Report

Project Team for Research Project

Colorado Water Conservation Board (CWCB)
Flood Protection & Weather Modification Permitting Section
Joe Busto, Project Manager

Denver Water (DW) Operational Cloud Seeding Program
Steve Schmitzer
Becky Dechant, Greg Bryant

Project Consultant to CWCB & DW
Curt Hartzell, CCM

Consultant to CWCB for GIS Support
Ross Williams

Cloud Seeding Operations for DW
Western Weather Consultants, LLC
Larry Hjermstad

Colorado State University Research Team
Dr. Bill Cotton, PI
Ray McAnelly, Gustavo Carrió, Paul Mielke, Brenda Thompson

September 2005

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIXES

Appendix 1 – WWC Cloud-seeding Generator Sites

Appendix 2 – NRCS SNOTEL Sites in Colorado

Appendix 3 – February 4, 2003 Seeding Test Case

Appendix 4 – WWC Daily Operational Notes

Appendix 5 – SNOTEL Observed & Model Control Simulated 24-hr Precipitation

Appendix 6 – Multivariate Randomized Block Permutation Evaluation Output

ACKNOWLEDGEMENTS

Numerous organizations and individuals have made significant contributions to this scientific study entitled, “Numerical Simulations of Snowpack Augmentation for Drought Mitigation Studies in the Colorado Rocky Mountains.” Although the Colorado Water Conservation Board (CWCB) staff was tasked with submitting the proposal on behalf of state of Colorado, bringing this project to fruition would not have been possible without the following agencies and individuals listed in subsequent paragraphs. Although not all of the project supporters can be acknowledged on this page, recognition of several of the more involved organizations and individuals is essential and appropriate. As population growth and reliance on Colorado’s water resources along the Front Range and outside our state borders continue to grow, we must seek a better understanding of harvesting atmospheric water resources for the benefit of current and future generations.

Curt Hartzell, Consultant to the Colorado Water Conservation and Denver Water, is a Certified Consulting Meteorologist and led the project team. Mr. Hartzell provided leadership and insight throughout the project. His proactive involvement from project scoping, submission of the proposal, to accomplishing the various work tasks, and writing the final report ensured that this study was completed and meaningful to the science of weather modification, the U.S. Bureau of Reclamation, the Colorado Water Conservation Board, and the Denver Water Board.

The other sponsoring agency that should be acknowledged is the Denver Water Board. Denver Water’s staff members Steve Schmitzer, Greg Bryant, and Becky Dechant helped fund the study and participated in meetings. Denver Water staff provided valuable information and organization as we mapped the project area for the analysis.

Dr. Bill Cotton of Colorado State University was the Principal Investigator for the study and his willingness to undertake this project with limited funding is commendable. His project team’s dedication to the study ensured we have taken a step forward for the science of evaluating weather modification through atmospheric modeling. Teaming atmospheric models to weather modification operations will be essential for future operational decisions and post-seeding evaluations. Dr. Cotton’s team of Ray McAnnelly, Dr. Gustavo Carrio, Brenda Thompson, and Paul Mielke, conducted all of the modeling and analyses, and the final results would not have been possible without their work.

It is also important to acknowledge Mr. Larry Hjermstad of Western Weather Consultants, LLC, who was a part of the project team throughout. Mr. Hjermstad is in fact “Mr. Colorado” when it comes to cloud seeding. He was Colorado’s first weather modification permit in 1972 and has operated

continuously through the Vail/Beaver Creek weather modification program for nearly thirty-three years. In addition he holds most of the wintertime weather modification permits in Colorado and has done much to develop and maintain "cloud seeding" programs in Colorado.

Ross Williams, a Geographic Information System (GIS) Specialist, was added to the study team and made new mapping and interpretive products available through building a detailed digital elevation model for the project area. This in turn gave us the ability to use GIS to map the target areas, generator locations, as well as more precisely display RAMS model output for added emphasis and understanding.

We would also like to thank the U.S. Bureau of Reclamation through its Weather Damage Modification Program for providing the funding to complete the modeling and evaluations. Reclamation staff members Dave Matthews (retired), Jon Medina (retired), and Steve Hunter were very cooperative and helpful in assisting the CWCB and CSU to bring this project idea to fruition.

Joe Busto
Colorado Water Conservation Board
Flood Protection Program & Weather Modification Permitting Program
1313 Sherman Street, Room 721
Denver, CO 80203
Phone: 303.866.4807
Fax: 303.866.4474
Email: joe.busto@dwr.state.co.us

COLORADO WEATHER MODIFICATION GRANT PROGRAM

Weather modification operations and research has been conducted in Colorado since the 1950s. The state of Colorado has had a weather modification permit program since 1972. Authority to administer the state's program resides within the Executive Director of Natural Resources, but has been delegated to the Colorado Water Conservation Board (CWCB) since 1987 and reaffirmed in 2001 and 2004 due to its connection to water resource management. The CWCB is the regulatory entity that is charged issuing and monitoring weather modification projects within the state.

CWCB directors, other state leaders, and river basin representative board members recognize the important role that cloud seeding can play in augmenting water supplies and has therefore supported a stable grant program and collaboration on scientific research projects. The weather modification grants provide some state cost share and help offset the weather modification permit fees that require the state of Colorado to collect 2% of the contract between the permit holder (contractors) and the project sponsor (water users). The state of Colorado Fiscal Year is July 1st through June 30th. In FY-04 the CWCB provided $20,000 in state cost-share grants through the Construction Fund (CF) Bill. In FY-05 $60,000 is being made available and for FY-06 $75,000 is requested. A conference call between the contractors and the CWCB in November 2004 solidified the criteria for equitable division of the grant funds for FY-05 and future years out. The issue centered around programs on standby vs. active status. The Telluride and Denver Water Programs both had valid permits, contracts for the year, and generators in place, but were not going to actively seed unless the good snowfall forecast for the 2004-2005 winter didn't materialize. It was decided that 5% of the grant money each year would be set aside and divided among standby programs, and 95% of the grant money would be divided among the active permits.

The CWCB was elected Vice Chair of the North American Interstate Weather Modification Council (Council) for 2004-2005. The nine Council Member states have also seen unprecedented growth in wintertime cloud seeding to augment snowpack in response to the western drought. Now more than ever, the Council states seek to coordinate efforts, share new developments, develop research funding, and secure leadership and funding from federal agencies. Now, more than ever reliance on Colorado as a "headwater state" with snowfields is a salient issue. This recent interest is important as is briefly accounted for below. In May 2005 the CWCB passed a Board resolution that conveys support for S.517, Senator Kay Bailey Hutchison's Bill to establish funding and a coordinated federal program. The CWCB resolution was sent to local and D.C. offices for Colorado's delegation (Ken Salazar, Hefley, Tancredo, Udall, DeGette, Beauprez, Musgrave, John Salazar). In June 2005 the CWCB attended the Western Governor's Association meeting and presented packet of information meant to encourage conversations among decision makers that included: a memo entitled “Large Scale WM Programs for Managing Water Supply”, a memo supporting this concept from NAIWMC Chair, Arlen Huggins (Desert Research Institute in Reno, Nevada), a snowpack map of April 1 Snow Water Equivalent in western states, a graphic of current programs, and a weather modification FAQ sheet. The snowpack map was meant to give some means to plan for and mitigate drought through enhanced wintertime weather modification.

Also In June 2005 Colorado Congressman Mark Udall responded to the CWCB request by the introduction of HR 2995 a companion bill to S. 517. In July 2005 as follow up to the CWCB request at the Western Governor’s Association meeting the Western States Water Council passed a resolution (position 264) supporting advancement in weather modification at a business meeting in Seattle, Washington. Also interesting was the WSWC position 265 that requests the $6 Billion in the Reclamation Fund be used as intended for water development projects. In August 2005 honoring Congressman Udall’s request the CWCB passed another weather modification resolution supporting both bills (HR 2995 and S. 517), requested more state representation on these “boards”.

Large scale weather nodification is being discussed at local, state and federal levels well. In August 2005 there was a Colorado 7-Basin States Meeting in San Diego, California. The issue revolves around low flow year criteria and operations within the Colorado River Basin related to Lake Powell and Lake Mead. All of the 7- Basin states were tasked with looking at some form of water augmentation activities like desalinization, reservoir operations, weather modification, and tamarisk control. Colorado and Utah will be working together to create a “weather modification white paper” that will ultimately be put together with other white papers and sent as a letter with recommendations to the U.S. Bureau of Reclamation and the Secretary of Interior Gale Norton.

Weather modification research and operations in “headwaters” states will become increasing important as approximately 80% of western states water comes directly from snowpack. Recently the CWCB conducted a study of current and future water needs in Colorado. The Statewide Water Supply Investigation (SWSI) forecasts water shortages in every major river basin and an inability to meet water needs by 2030; in fact very few water providers have identified water supplies beyond 2030. The SWSI process identified tremendous pressure on agriculture to meet current and future municipal water demands. In addition, the SWSI process identified an 80% - 20% solution/problem. This means that even if the most optimistic scenario unfolds and water users are able to implement all available and known water resource projects and programs, they could at best meet 80% of their future water needs. This leaves 20% of our needs unmet and there clearly is a problem. Weather modification research and operations in basins above areas with forecasted population growth and water shortages has the ability to keep agriculture viable and provide an economical means of developing water resources to meet current and future needs. Everything is connected and development and population growth will change the face of the landscape in Colorado. Additional information on the SWSI is on the CWCB's Web site http://cwcb.state.co.us/SWSI/Table_of_Contents.htm.

In conclusion it is fair to say that everything is connected, water is life, and much of it originates form our mountainous areas interaction with our storm systems and snowfields. Colorado's economy is heavily based on recreation and agriculture, both heavily reliant on good water years. The Rocky Mountain News has recently embarked on a four-part news story that is based solely on the research in the "Rocky Mountain/Great Basin Regional Climate Change Assessment" conducted by 125 researchers that involved climate modeling and the effects of global warming. Based on interpretation of the study it paints a gloomy future for Colorado's $2 billion ski industry and rafting industry. Colorado skiing could be affected by warmer conditions, shorter seasons, making it difficult on low elevation ski areas and this might lead to a heavy reliance on the water used for artificial snowmaking. We ski on our water, then we raft on our water, then it fills our streams and reservoirs. Once used this water returns to rivers and streams to meet needs in other states. Investing in the understanding, development, and augmentation of snowfields through weather modification in a headwaters state like Colorado will be imperative to surviving in the arid western United States.

The Colorado WDMP "Numerical Simulations of Snowpack Augmentation for Drought Mitigation Studies in the Colorado Rocky Mountain" project conducted and collaborated on by Reclamation, Denver Water, CWCB, and CSU is the type of applied research project needed to work toward developing the efficacy and understanding of weather modification operations. Weather modification research that is piggy-backed onto existing operations provides the best means to advance weather modification operations. Wintertime operational weather modification projects should be designed for refinement and development with the goal of maximizing Colorado's water resources to meet current and future needs.

EXECUTIVE SUMMARY

The Colorado Weather Damage Modification Program (WDMP) research project involved a physical evaluation of the Denver Water (DW) operational winter orographic cloud seeding program in the central Colorado Rockies for the winter season 2003-2004 using the Colorado State University mesoscale Regional Atmospheric Modeling System (RAMS). The project was piggy-backed onto the DW operational program contracted by Western Water Consultants (WWC), LLC. The target area was the Blue, Upper Blue, Snake, Williams Fork, and Upper South Platte River drainage basins above 9,000 feet elevation (see Figure 2.1). The area within the target boundary was about 3,700 km^2. From February 10 through March 2004 only the Upper South Platte River basin and along the Continental Divide above the Upper Blue River basin was to be targeted. Using a finest grid spacing of 3-km, RAMS was run first in real-time to provide operational support to the DW cloud seeding program. RAMS was subsequently rerun for the period of operations with a number of improvements derived from assessments of the real-time runs, and then rerun with simulated seeding generators releasing seeding material (AgI) at rates, time periods, and locations consistent with the operational program.

As a mesoscale model, RAMS is unique in its ability to explicitly represent the activation of cloud nucleating aerosols (CCN and IN) including seeded IN, to simulate the transport and dispersion of seeding material, the explicit nucleation and vapor deposition, riming, and aggregation growth of ice particles, and amounts and types of precipitation. Moreover, it was able to do so for an entire operational cloud seeding program. We believe that this project establishes a "model" of a methodology for physical and statistical evaluation of future seeding projects. However, it must be recognized that this was a first prototype model and as such things did not work out entirely according to our expectations.

The major results of this research project are as follows:

- WWC (Larry Hjermstad) found that after the model fixes had been implemented in mid-February 2004 and the RAMS real-time forecast 0000 UTC cycle was run on the new PC cluster, the forecast output that was posted on the Web site was very useful. The low-level warm temperature problem had been greatly reduced and the model provided timely input for operational cloud seeding decision making. There were numerous forecast products and parameters to evaluate. In addition to the 2-hr forecast presentations, the animated forecast loops provided a quick visual picture of changes over time.
- Larry Hjermstad did point out the forecast model exhibited a warm temperature bias at 700 mb which reduced its effectiveness as a decision tool for determining if seeding operations should proceed. Causes of the warm bias were determined and fixes were made in mid-February 2004. The entire winter season was re-run to provide a better estimate of natural

and seeded precipitation. However, the model fixes did not entirely eliminate the low-level warm bias.

- The best 30 cloud-seeding days were selected for use in post-season research evaluations. When compared to measured 24-hr precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88. The highest bias areas included the Target Area. The lowest bias areas were in more upwind areas in northwesterly and southwesterly events. Possible sources of those biases are discussed in the text and are currently still under investigation.
- The model control simulations produced a reasonable qualitative pattern of total precipitation and its topographic dependence for the 30 selected days. The 30-day simulated precipitation total showed only light precipitation over the entire SE leg and south half of the SW leg of the target area. Thus the model suggests little orographic precipitation potential and perhaps little cloud seeding potential over the two south legs of the target area.
- The model forecast precipitation data were evaluated against SNOTEL data using MRBP statistical analysis procedures. The results from the evaluation show that the model is describing the non-seeded and seeded simulation equally well. While the signal of the fits is strong (all P-values about 1.0E-6 or less), the agreement measures are not outstanding (all fall between 0.18 and 0.26).
- Comparison of model-predicted precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals (difference of -1.0 mm) or the 30 days selected for model precipitation evaluation seed and control average totals (difference of -0.2 mm).
- Langrangian trajectory analyses of six selected days of the subset of 30 days selected for precipitation evaluation revealed that particles are generally being transported to the target area by the targeting wind as intended. On average, 54% of those particles are 50-500 m AGL, with another 34% in the layer 500-1000 m AGL, which are levels suitable for AgI seeding.
- The Lagrangian analyses confirm that generators should not be used when the targeting wind would not carry their plumes over the target area. Low level trapping of particles can become moderate in nocturnal inversions, but significant numbers of particles escape the inversions and are transported by the targeting wind as intended. It appears that generators located on the lee side of mountain ranges may be in stagnation zones or rotors associated with high amplitude mountain waves, and their particles are also subject to moderate local trapping.

The very small differences between seed and control precipitation predicted by the model were very disappointing and not expected at the onset of this project. Possible causes of such low seedability:

- The model predicted seedability could be real; however, because of the model over precipitation prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- The background CCN and IN concentrations are unknown but instead are determined by our selected background concentrations. Too low a background CCN concentration would make clouds more efficient in natural precipitation formation thereby lowering seedability. Too high background IN concentrations would likely lead to lower seedability.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby lowering seedability.
- The evaluated over-prediction bias in precipitation may lead to reduced opportunities for precipitation enhancement in the model.
- Banded patterns of seed - no seed differences on daily totals suggest a possible dynamic response to seeding. This pattern of differences results in much of the target area being in regions of reduced precipitation.
- The low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent. However, this effect has overall a small impact on seedability.
- The simulated transport and diffusion of seeding material from the generator sites is getting into the clouds too far downwind of the generate sites. However, the particle modeling suggests that seeded material is delivered to the target area at levels suitable for seeding, which argues against the notion that seeding material is not getting into the intended seeding zones.

It is recommended that, because this was only a one-year contract and research funding was limited, additional modeling studies are warranted. One of the first things that needs to be done is to determine the cause of the model over-prediction bias in precipitation. Another is to explore the various hypotheses that have been put forward to explain the very small differences between seed and no-seed precipitation amounts. Still another area to explore is the almost non-existent SLW in the 2-hr vertically integrated maps over the target area; additional sensitivity tests would be useful. Also, it would also be desirable to rerun all or at least the 30 selected days with higher resolution to determine if increased resolution reduced the precipitation bias and/or the seed, no-seed differences.

In support of future operational cloud seeding projects in which a model is used as part of the evaluation technique, it is urged that background CCN and IN concentrations be measured. Preferably this would be airborne but in lieu of that longer term ground-based measurements, particularly from higher-terrain sites would be desirable. Other items that would be very useful on such a project would be a vertically-pointing radiometer near the summit on the target mountain barrier for SLW detection, and the use of scanning cloud radar for identifying regions of liquid water in the clouds and to follow precipitation morphology. In addition the combination of model predictions and new observations such as cloud radar and radiometers could be used in a very sophisticated method of evaluation of an operational seeding project.

GLOSSARY AND ACRONYMS

Accretion: In cloud physics, the growth of an ice hydrometeor by collision with supercooled cloud drops that freeze wholly or partially upon contact.

AgI: Silver Iodide

AGL: Above Ground Level

AMS: American Meteorological Society

ATMET: ATmospheric, Meteorological and Environmental Technologies

CCM: Certified Consulting Meteorologist

CCN: Cloud Condensation Nuclei – particles, either liquid or solid, upon which water vapor condenses and forms cloud drops in the atmosphere.

CFDC: Continuous Flow Diffusion Chamber

CLW: Cloud Liquid Water – the amount of non-precipitation liquid water in a cloud, usually measured in gm^{-3}.

CRBPP: Colorado River Basin Pilot Project

CSU: Colorado State University

Cloud seeding: The introduction of agents (e.g. silver iodide) into a cloud to alter the phase and size distribution of cloud particles for the purpose of modifying its development or increasing its precipitation.

CoCoRaHS: Community Collaborative Rain, Hail & Snow network in Colorado

Cold cloud: A cloud composed of supercooled water drops and/or ice particles.

Condensation: The physical process by which a vapor becomes liquid; the opposite of evaporation.

Convection: As specialized in meteorology, atmospheric motions that are predominantly vertical, resulting in the vertical transport and mixing of atmospheric properties; distinguished from advection.

Convective cloud: A cloud which owes its vertical development, and possibly its origin, to *convection*.

CWCB: Colorado Water Conservation Board

Deposition: The physical process that occurs in subfreezing air when water vapor changes directly to ice without becoming a liquid first; the opposite of sublimation.

DW: Denver Water department

Eta model: operational from NOAA (see NAM)

ESRI: Environmental Systems Research Institute

FY: Fiscal Year

GCCN: Giant Cloud Condensation Nuclei (dry particle diameters > 6 microns)

GIS: Geographic Information System

Glaciogenic seeding: Process of enhancing ice content in cold clouds containing supercooled liquid water by nucleating new crystals.

Ground generators: In weather modification, usually refers to silver Iodide (AgI) smoke generators that are operated from the ground (as opposed to airborne equipment).

ID: Identification

IFN: Ice Freezing Nuclei

IN: Ice Nuclei

in: inch

km: kilometer

knot: a unit of speed in nautical miles per hour (1 mph = 0.8684 knot; 1 m/sec = 1.9425 knots)

Low: closed low pressure area

mb: abbreviation for millibar; a pressure unit of 1000 dynes per cm^2, convenient for reporting atmospheric pressures.

mm: millimeter (1 inch = 25.40 mm)

MRBP: Multivariate Randomized Block Permutation

MSL: Mean Sea Level

MST: Mountain Standard Time

NAM (formerly Eta) model: North American Meso operational model from *NOAA*'s National Centers for Environmental Prediction (NCEP).

NAS: National Academy of Sciences

NCEP: National Centers for Environmental Prediction

NOAA: National Oceanic and Atmospheric Administration

NRCS: Natural Resources Conservation Service

Nucleation: The initiation of a phase change of a substance to a lower thermodynamic energy state (i.e., vapor to liquid *condensation*, vapor to solid *deposition*, or liquid to solid *freezing*).

Nuclei: A particle of any nature upon which, or the location at which, molecules of water or ice accumulate as a result of a phase change to a more condensed state; an agent of *nucleation*.

NWS: National Weather Service

Orographic cloud: A cloud whose form and extent is determined by the distributing effects of orography (i.e., mountains), which causes lifting and condensation in the passing flow of air. Because these clouds are linked to the terrestrial relief, their location changes very slowly, if at all.

Overseeding: Condition in a cloud where an excess of nuclei are available, thereby creating a competition for the available cloud droplets or water vapor, possibly preventing any of them from growing to the appropriate size necessary to reach the ground.

PC: Personal Computer

PI: Principal Investigator

RAMS: Regional Atmospheric Modeling System

Rawinsonde: A method of upper-air observation consisting of an evaluation of the wind speed and direction, temperature, pressure, and relative humidity aloft by means of a balloon-borne radiosonde tracked by a radio direction-finder.

Reclamation: United States Department of the Interior, Bureau of Reclamation

SNOTEL: SNOpack TELemetry

Snowpack: The amount of snowfall that remains on the ground at higher elevations in the mountains; measured in snow depth and *snow water equivalent*.

Static seeding: A strategy for optimum *nucleation*; exploiting the preexisting situation where less-than-optimal ice crystal concentrations exist, which leads to prolonged periods of *supercooled water*, with no attempt to modify the dynamics of the seeded clouds.

SWE: Snow Water Equivalent

SLW: Supercooled Liquid Water - in cold clouds, drops of liquid water colder than the nominal freezing point for water (0°C or 32°F).

TKE: Turbulent kinetic energy

Tropa: weather system Trough passage

URL: Uniform Resource Locator – the global address of documents and other resources on the World Wide Web.

UTC: Universal Coordinated Time

WDMP: Weather Damage Modification Program

WMA: Weather Modification Association

WMO: World Meteorological Organization

WWC: Western Weather Consultants

Z time: The letter identifying the “Zulu” time zone centered on the Greenwich Prime Meridian. By international agreement, the reported times for essentially all meteorological reports are given according *to Universal Coordinated Time (UTC)*.

1. INTRODUCTION

1.1 Weather Damage Modification Program

In August 2003, the Colorado Department of Natural Resources, Water Conservation Board received a solicitation (No. 03-FC-81-0890) and a request for proposal for the *Weather Damage Modification Program for Cooperative Weather Research between States and the U.S. Department of Interior, Bureau of Reclamation*. State government offerors had to be willing to cost-share 50% or more of the project costs, as well as identify an existing operational program that would allow the proposed research to be “piggy-backed” onto operational cloud seeding activities. Federal funds could only be used for research equipment, data collection, modeling, analysis, and reporting. The solicitation specified that each state’s basic proposal could not request a Bureau of Reclamation (Reclamation) cost share in excess of $100,000.

The goal of the Weather Damage Modification Program (WDMP) was to improve and evaluate physical mechanisms to limit damage due to weather phenomena such as drought and hail, enhance water supplies through a regional weather modification program, and to transfer validated technologies for implementation on operational programs. The WDMP was designed to produce those new technologies by funding scientific research proposals submitted by state agencies having operational programs.

The Colorado Department of Natural Resources, Water Conservation Board (CWCB) submitted a proposal for the state of Colorado. The proposal was for a research project titled *Numerical Simulations of Snowpack Augmentation for Drought Mitigation Studies in the Colorado Rocky Mountains*. The proposed research project was “piggy-backed” onto the Denver Water (DW) operational winter orographic cloud seeding program in the central Colorado Rockies. The project proposed to provide a physical evaluation of the DW operational program by using the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS). The CWCB and DW proposed to hire an experienced meteorological consultant to assist in the project management, technical reviews, and the reporting task. The proposal was successful and funded by a $100,000 grant Financial Assistance Agreement (No. 03-FC-81-0925) from Reclamation dated 2 October 2003.

1.2 Project Administration and Management

The WDMP Grant received by the CWCB from Reclamation funded all of the RAMS related research activities by the CSU team. All other costs (project management, project administration, scientific and technical consultant, GIS support, and operational cloud seeding activities) were covered by the CWCB and DW, which more than met the Solicitation’s 50-50 cost sharing requirement.

Mr. Joe Busto, CWCB Flood Protection and Weather Modification Permitting Section, served as the Project Manager for the Colorado WDMP research project. He was the point of contact between the CWCB and Reclamation, and procured the services of Mr. Ross Williams for GIS support. He oversaw the administration of the grant funds at the CWCB, and the related Interagency Agreement with CSU. He also participated in research project coordination and meetings with Reclamation, CSU, and DW.

Mr. Curt Hartzell, CCM, assisted Joe Busto in the program management, closely overseeing activities to ensure that the program objectives were being achieved. He coordinated project activities between the CWCB, the CSU research team, the DW Operational Cloud Seeding Program (Mr. Steve Schmitzer), and the DW program's cloud seeding contractor, Western Weather Consultants, LLC (Mr. Larry Hjermstad).

Dr. Bill Cotton was the Principal Investigator (PI) for the CSU research team (Mr. Ray McAnelly, Dr. Gustavo Carrió, Dr. Paul Mielke). Administrative assistant Ms. Brenda Thompson monitored all CSU work task expenditures, prepared and submitted invoices to the CWCB, and helped in the preparation of project reports.

1.3 Current Status of Winter Orographic Cloud Seeding

There is ample evidence that seeding cold orographic clouds containing supercooled liquid water with a chemical agent such as silver iodide can form ice crystals that may fall as snow. Water managers can be at least cautiously optimistic that a viable technology is emerging for seeding winter orographic clouds for snowfall increase – if the seeding program is properly designed and conducted.

The most recent policy statement on weather modification by the American Meteorological Society (1998) states that, "There is statistical evidence that precipitation from supercooled orographic clouds (clouds that develop over mountains) has been seasonally increased by about 10%. The physical cause-and-effect relationships, however, have not been fully documented. Nevertheless, the potential for such increases is supported by field measurements and numerical model simulations."

The recently updated (2005) Weather Modification Association (WMA) *Capability Statement on Weather Modification* includes the following: "The capability to increase precipitation from wintertime orographic cloud systems has been demonstrated successfully in research experiments… Technological advances have aided winter precipitation augmentation programs. Fast-acting silver iodide ice nuclei, with higher activity at warmer temperatures, have increased the capability to augment precipitation in shallow orographic cloud systems. Numerical modeling has improved the understanding of atmospheric transport processes and allowed simulation of the meteorological and microphysical processes involved in cloud seeding." However, the level-of-evidence issue regarding estimations of winter orographic cloud seeding effectiveness remains a topic of debate. Objective evaluations of non-randomized operational cloud seeding programs continue to be a difficult challenge.

The World Meteorological Organization (WMO) recognized the potential of cloud seeding in favored locations in a statement on the status of weather modification issued in Geneva in June 2001. That statement says under *orographic mixed-phase cloud systems*: "In our present state of knowledge, it is considered that the glaciogenic seeding of clouds formed by air flowing over mountains offers the best prospects for increasing precipitation in an economically-viable manner. These types of clouds attracted great interest in their modification because of their potential in terms of water management, i.e. the possibility of storing water in reservoirs or in the snowpack at higher elevations. There is statistical evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of surface precipitation records from some long term projects indicate that seasonal increases have been realized." Operational cloud seeding programs aimed at enhancing precipitation exist in more than 24 countries (see Figure 1.1).

SOURCE: WORLD METEOROLOGICAL ORGANIZATION

Figure 1.1. Countries with active cloud seeding programs

In the 2003 National Academy of Sciences (NAS) report entitled *Critical Issues in Weather Modification Research,* the Committee concluded for weather modification in general, "there still is no convincing scientific proof of the efficacy of intentional weather modification efforts… This does not challenge the scientific basis of weather modification concepts. Rather it is the absence of adequate understanding of critical atmospheric processes that, in turn, lead to a failure in producing predictable, detectable, and verifiable results." However, in a more positive conclusion the Committee noted, "There are strong suggestions of positive seeding effects in winter orographic glaciogenic systems."

The NAS report (2003) recommends a coordinated research effort and lists a few especially promising possibilities where substantial further progress may occur, including, "*Orographic cloud seeding to enhance precipitation*. Such a program could build on existing operational activities in the mountainous western United States. A randomized program that includes strong modeling and observational components, employing advanced computational and observational tools, could substantially enhance our understanding of seeding effects and winter orographic precipitation." Such a research program is needed, but as Professor Roland List noted (2005), it should be understood that the only reliable statements made in randomized experiments are statistical in nature. Statistics do not give "scientific proof" of anything, it only gives a measure of the outcome, such as the confidence level.

Within the United States, there are over 65 operational weather modification programs in 10 western states; no federal funding currently is supporting any of these operational activities. The NAS report (2003) states, "Despite the large number of operational activities, less than a handful of weather modification research programs are being conducted worldwide. After reaching a peak of $20 million per year in the late 1970s, support for weather modification research in the United States has dropped to less than $500,000 per year." Currently scientists have the knowledge and tools to advance the field of winter orographic cloud seeding for the benefit of water users, but not the research funding to fully verify the technology. In order to identify the optimum conditions and methodologies for winter orographic cloud seeding operations, all such programs in Colorado (and elsewhere) should include a well-defined research component to the extent funding will allow.

1.4 Colorado Weather Modification Permit Program

The state of Colorado has had a weather modification-permitting program since 1972. Authority for this program resides in the Executive Director's Office of the Colorado Department of Natural Resources. Since 1987, this authority has been delegated to the Director of the CWCB. The CWCB's Flood Protection Section has been administering Colorado's program for issuing permits for cloud seeding activities since 2001. For the 2003-2004 winter season, there were nine active permits for ground-based wintertime precipitation enhancement programs.

During the winter of 2003-2004 approximately 25-30 percent of Colorado's snowfields were in target areas for wintertime operational cloud seeding programs. These programs may hold the potential to significantly increase Colorado's headwater streamflows from the melt-off of enhanced winter snowpack. The CWCB weather modification permit program Web site is http://www.cwcb.state.co.us/Weather_Modification/Permit_Program.htm.

State Authorities (CRS 36-20-101): The CWCB has operated the Weather Modification Permitting Program under direction from the Executive Director's Office – Department of Natural Resources since 1987. A letter from Greg Walcher, Executive Director, dated August 2002, reaffirmed that agreement and directed the CWCB to conduct hearings and make initial recommendations to the Executive Director's Office for final approval. The CWCB acts as the state level regulator of programs, issues permits and monitors them for compliance with program rules and regulations and state statutes based on: the 1951 Weather Modification Act, the 1972 Weather Modification Act, HB 92-1018, HB 92-1129, and SB 96-90. The state has had a weather modification-permitting program since 1972. CWCB staff member Joe Busto was delegated the responsibilities for this program in July 2002 by Director Rod Kuharich.

- In order to conduct weather modification activities in Colorado you need to have a permit. In 1996 the Colorado legislature made the issuance of a permit contingent on the following requirements:
- You must have a permit to modify the weather in Colorado
- Permits are issued for specific projects
- The person in control of the project must be qualified
- Permits are for 5 consecutive years and are renewable
- The permit fee is $100 plus a 2% commercial fee
- Use Form WM-1 (qualifications) and Form WM-2 (project details) to apply
- Applications should be submitted at least 45 days before before the beginning of the project
- You must publish a public notice of intent to modify the weather
- A public hearing is required

1.5 Denver Water Operational Cloud Seeding Program

Due to continuing drought conditions in the central Colorado Rocky Mountains, in the fall of 2002 Denver Water (DW) contracted with Western Weather Consultants, LLC (WWC) to expand the Vail/Beaver Creek (BC) Ski Resort Program to the east and southeast to cover the watersheds within DW's water collection system. The DW 2002-2003 Program's target area included the Blue, Fraser, Williams Fork, and Upper South Platte River basins above 9,000 feet elevation.

The DW 2002-2003 Program consisted of 43 manually-operated cloud-seeding generators (38 new generator sites plus 5 existing generator sites from the Vail/BC Program). Cloud-seeding activities were performed from early November 2002 through April 7, 2003. There were a total of 25,433 hours of seeding at an average seeding rate of 5.92 grams of silver iodide (AgI) per seeding hour. Summary information on independent evaluations of the DW 2002-2003 Program is at http://www.denverwater.org/could_seeding.html.

1.6 Colorado State University Regional Atmospheric Modeling System

The Regional Atmospheric Modeling System (RAMS) was developed at Colorado State University (CSU). RAMS has been used at CSU for real-time forecasting since 1991 (Cotton et al., 1994). Gaudet and Cotton (1998) showed that explicit bulk microphysics improved the forecasting of the areal extent and maximum amount of precipitation, especially when compared to the SNOTEL automatic pillow-sensor stations, which are found at locations more representative of the model topography. For the month of April 1995, a series of 24-hour accumulated precipitation forecasts was generated with both the dump-bucket and microphysics versions of the forecast model. Both sets of output were compared to a set of 167 community-based station reports, and to a set of 32 SNOTEL stations. Climatological station precipitation forecasts were improved on the average by correcting for the difference between a station's actual elevation and the cell-averaged topography used by the model.

The model had more problems with the precise timing and geographical location of the precipitation features, probably due in part to the influence of other model physics, the failure of the model to resolve adequately wintertime convection events, and lack of mesoscale detail in the initializations. Wetzel et al. (2003) further demonstrated RAMS accuracy in predicting snowfall amounts in high-mountain terrain, specifically the Park Range of Colorado. As in the Gaudet and Cotton (1998) study, the best agreement occurred at the higher elevation sites and the worst in the valleys. This could be related to the inability of the model to represent the valley features correctly since emphasis is placed on getting the mountain high terrain forcing in the model. In addition, RAMS exhibited a warm-temperature bias, which may be a consequence of using Eta model forecast data for initialization and nudging: the Eta model is known to have such a warm temperature bias.

The 2003-2004 prototype real-time forecast version of RAMS@CSU was based on version 4.3. The physics of the model is described in some detail in Cotton et al. (2003). The model was set up on a cluster of PCs. The forecast model configuration has three interactive nested grids. Grid 1 has 48-km grid spacing that covers the entire conterminous United States. Grid 2 has 12-km grid spacing that covers all of Colorado, most of Wyoming, and portions of adjacent states. Grid 3 has 3-km grid spacing for 82 x 82 grid points covering a 246 km x 246 km area (60,516 km^2) that is relocateable anywhere within Grid 2. Figure 1.2 shows RAMS Grid 1 covering the contiguous U.S. with nested Grids 2 and 3. Figure 1.3 shows the 12-km regional grid, and Figure 1.4 shows the 3-km fine grid with the project target area and some town IDs.

Vertical grid spacing on all grids starts with 150-km spacing at the lowest levels and is stretched to 1000 m aloft, with a total of 36 vertical levels extending into the stratosphere. The model is initialized with 0000 UTC Eta model analysis fields and run for a period of 48 hours, with the lateral boundary region of the coarse grid nudged to the Eta 3-hr forecast fields. A 48-hr run typically begins at 0300 UTC (2000 MST) when the 0000 UTC Eta forecast data are available. The run takes 4-5 hours of computer time to finish, and is completed by 0200 MST. Because RAMS has been able to reproduce high-elevation snowfall amounts with considerable accuracy (Gaudet and Cotton, 1998; Wetzel et al., 2003), it was believed that RAMS could be useful in forecasting the effects of cloud seeding on precipitation for an entire winter season.

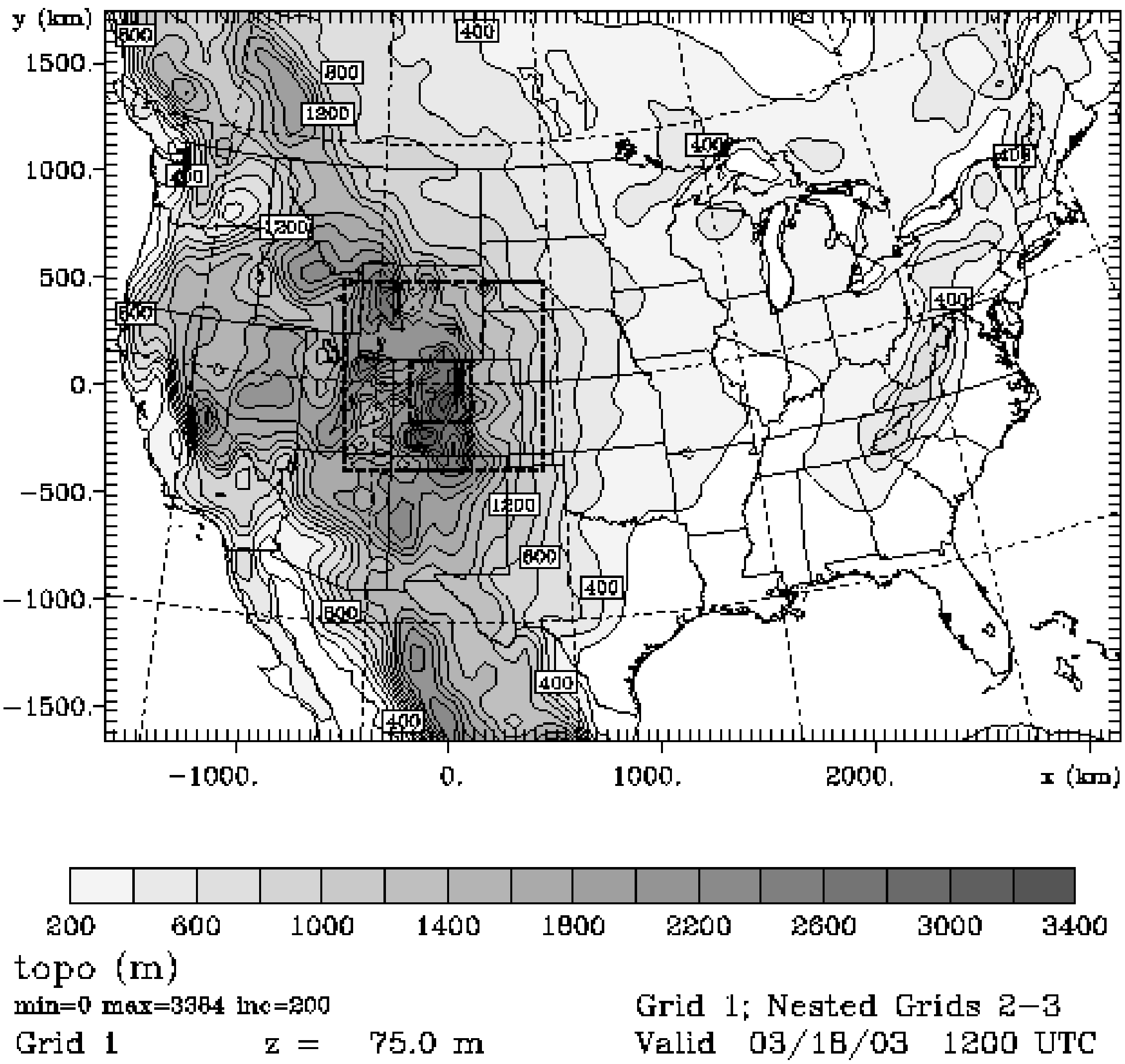


Figure 1.2. RAMS Grid 1 (48-km parent grid with nested Grid 2 and Grid 3)

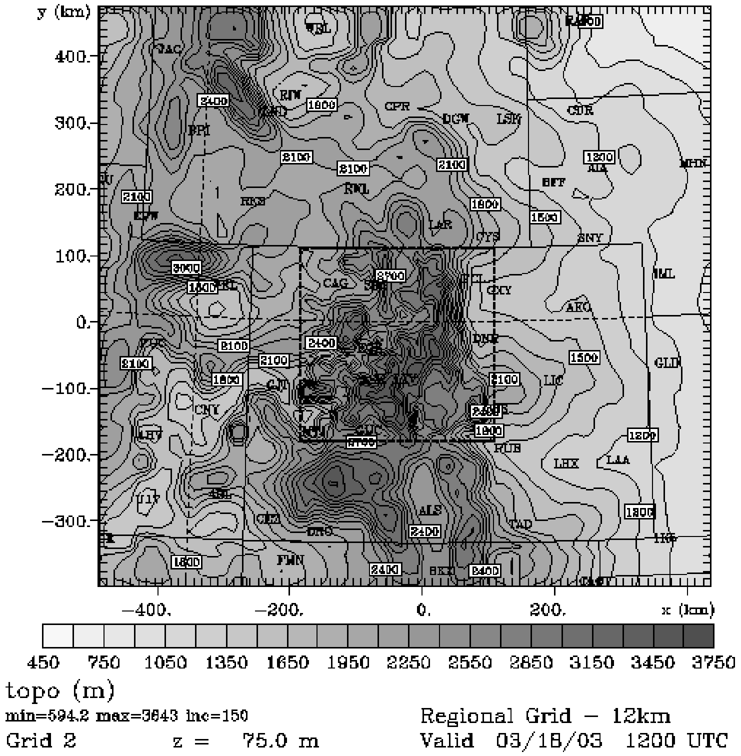


Figure 1.3. RAMS Grid 2 (12-km regional grid)

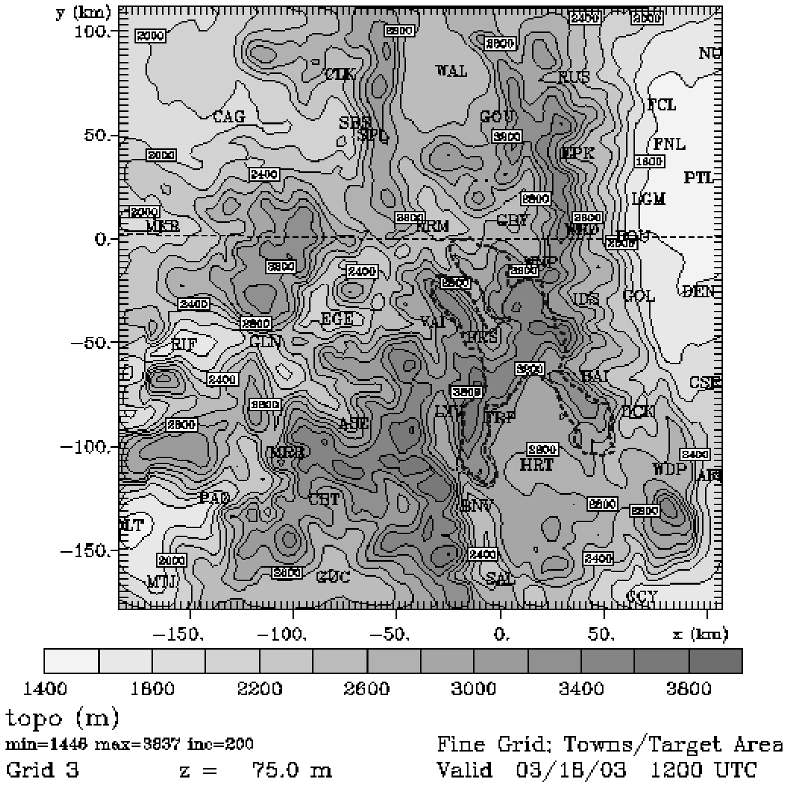


Figure 1.4. RAMS Grid 3 (3-km find grid with target area)

2. PROJECT OVERVIEW

2.1 Colorado WDMP Research Project Goal and Objectives

The Colorado Weather Damage Modification Program (WDMP) research project was joined with the Denver Water (DW) operational orographic cloud-seeding program in the central Colorado Rocky Mountains for the 2003-2004 winter season. The goal for the research project was to provide a physical evaluation of the operational winter glaciogenic seeding of orographic cloud systems using the well-established Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS).

The objectives for the research program were to use RAMS to develop a better understanding of the transport and dispersion of seeding materials, and to provide guidance as to what meteorological conditions are most favorable for augmenting snowfall from winter orographic cloud systems over the central Colorado Rocky Mountains. It was not the purpose of this research project to provide a definitive evaluation of the DW 2003-2004 program's cloud-seeding effects. Rather, RAMS was to be used in real-time operational forecasts, and in post-season studies simulating cloud seeding to provide indications for seeding effects and the types of meteorological conditions favorable for glaciogenic seeding.

2.2 Denver Water 2003-2004 Operational Cloud-seeding Program

In September 2003, the Denver Water department contracted with WWC for cloud-seeding activities. For the November 2003 through February 10, 2004 period the program target area was the Blue, Upper Blue, Snake, Williams Fork, and Upper South Platte River basins above 9,000 feet elevation. The Blue River basin is upstream of Green Mountain Reservoir, and includes all streams feeding Dillon Reservoir, except Tenmile Creek. The location of the intended target area for the DW 2003-2004 Program is shown in Figure 2.1. The area within the target boundary was about 3,700 km^2. From February 10 through March 2004 only the Upper South Platte River basin and along the Continental Divide above the Upper Blue River basin was to be targeted.

A total of 39 cloud-seeding generators were used for the DW 2003-2004 Program (33 from the DW 2002-2003 Program plus 6 from the Vail/Beaver Creek Program). Four of the DW Program seeding generators were also used for the adjoining Upper Arkansas River basin program. These 39 WWC cloud-seeding generator sites are listed in Appendix 1. This appendix includes a map showing the locations of the sites in relation to the DW Program's target area. Another change was that the average seeding rate from the 2002-2003 winter cloud-seeding activities was to be increased by about 50%. The funding level for DW's 2003-2004 cloud-seeding program was $400.000.

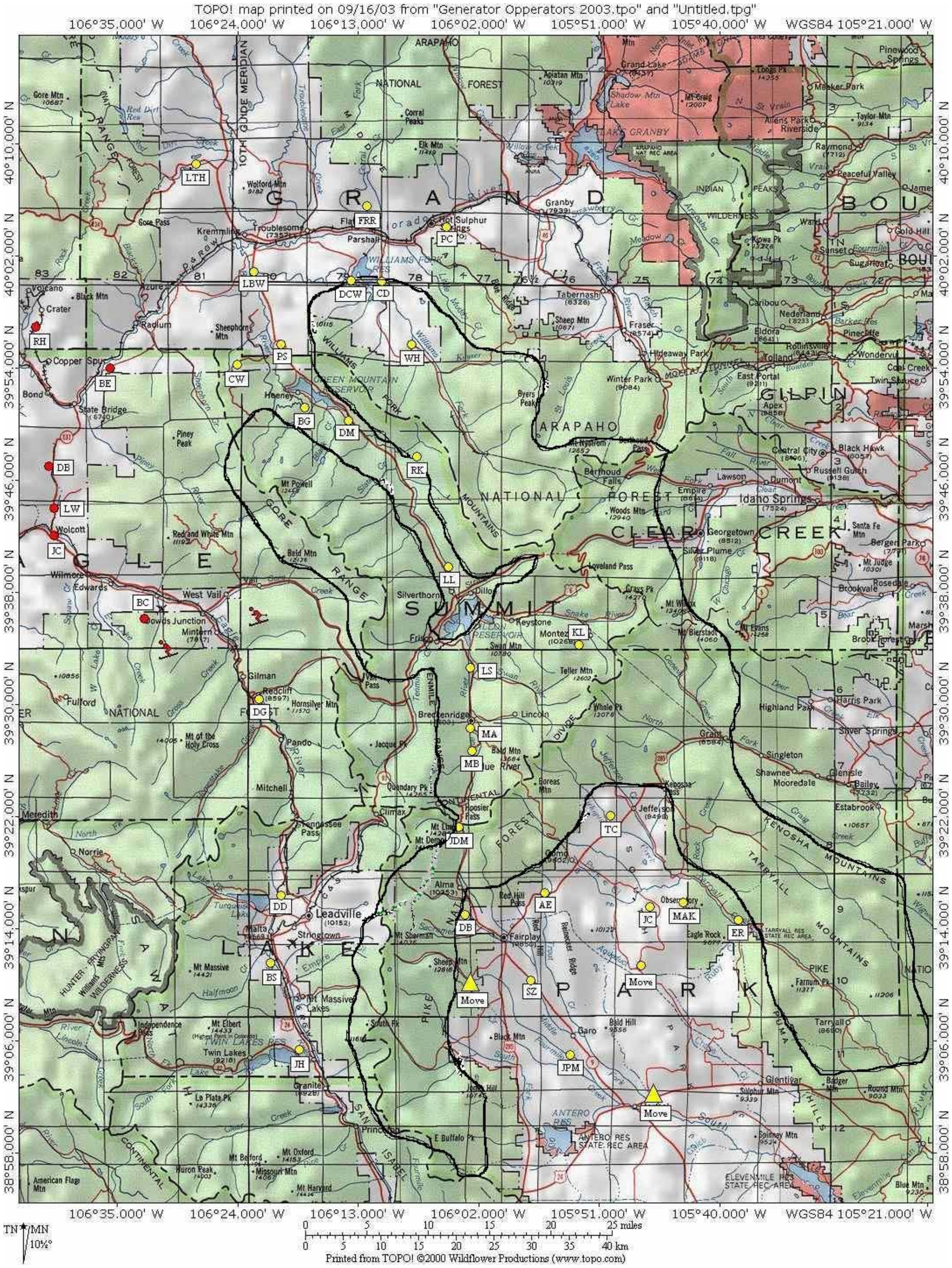


Figure 2.1. Intended target area for the DW 2003-2004 Program

The DW 2003-2004 Program conducted cloud-seeding activities on 29 winter orographic cloud systems over portions of 75 calendar days for a total of 14,768 seeding hours. These operational cloud-seeding events are listed in Table 2.1. The average seeding rate was 8.45 grams of silver iodide (AgI) per seeding hour, which was a 43% increase in the average seeding rate from the DW 2002-2003 Program. The reason that a 50% average seeding rate was not achieved was because WWC's cloud-seeding activities for the DW Program's 2003-2004 winter season were skewed towards more frequent and longer operations during the colder portion of the winter season when lighter seeding rates are normally used. Figure 2.2 is an example of a WWC generator site used for both the DW Program and the Vail/BC Program. The generator is in an exposed location that should allow the low-level wind flow to transport the AgI seeding nuclei toward downwind higher topography with orographic clouds.

Figure 2.2. WWC seeding generator site V1, elevation 7,088 ft, looking SE.

Table 2.1. Operational Cloud Seeding Summary for DW Program

DW & Vail/DW Operational Seeding Summary for 2003-2004 Season

Note: The Vail/DW data are for Vail seeding generator sites used for the DW Program.

Operational Seeding Summary			Parts of Days	Vail/DW Seeding Hours	DW Seeding Hours	V/DW+DW Seeding Hours	AGI Output (grams)	Grams per Hr.
Event No.	**From Date Time**	**To Date Time**						
1	11/2/03 17:30	11/4/03 12:00	3	41.00	519.75	560.75	8,316.00	14.83
2	11/5/03 8:30	11/6/03 16:30	2	56.75	380.00	436.75	5,060.00	11.59
3	11/7/03 8:30	11/8/03 18:00	2	41.75	105.75	147.50	846.00	5.74
4	11/10/03 7:30	11/12/03 9:00	3	122.75	742.00	864.75	7,010.50	8.11
5	11/13/03 7:00	11/15/03 9:00	3	101.50	679.75	781.25	8,156.00	10.44
6	11/16/03 21:30	11/18/03 11:00	3	79.50	387.00	466.50	3,860.50	8.28
7	11/22/03 8:00	11/23/03 12:00	2	24.00	232.75	256.75	2,315.50	9.02
8	11/25/03 10:00	11/27/03 13:00	3	88.75	619.50	708.25	4,730.50	6.68
9	12/7/03 8:30	12/9/03 16:00	3	78.25	686.25	764.50	6,837.00	8.94
10	12/10/03 23:00	12/12/03 22:00	3	90.50	448.50	539.00	2,766.00	5.13
11	12/13/03 9:30	12/15/03 23:00	3	69.25	650.75	720.00	5,180.25	7.19
12	12/21/03 8:00	12/22/03 18:30	2	63.50	498.00	561.50	4,205.50	7.49
13	12/25/03 23:00	12/28/03 10:00	4	58.75	615.25	674.00	4,620.50	6.86
14	12/29/03 21:30	12/31/03 11:30	3	86.50	321.00	407.50	2,185.50	5.36
15	1/1/04 21:30	1/4/04 9:30	4	72.00	869.00	941.00	7,411.00	7.88
16	1/16/04 10:30	1/17/04 9:00	2	0.00	498.75	498.75	3,559.00	7.14
17	1/19/04 21:30	1/21/04 9:00	3	0.00	588.75	588.75	4,772.00	8.11
18	1/25/04 7:00	1/25/04 23:00	1	24.25	334.25	358.50	2,588.00	7.22
19	1/28/04 7:45	1/29/04 23:00	2	51.00	417.00	468.00	3,410.00	7.29
20	1/30/04 20:30	2/1/04 14:00	3	43.50	849.75	893.25	7,896.00	8.84
21	2/3/04 10:00	2/6/04 10:00	4	22.00	1,167.50	1,189.50	8,887.00	7.47
22	2/7/04 21:00	2/9/04 23:00	3	28.50	659.00	687.50	5,606.50	8.15
23	2/11/04 8:00	2/11/04 23:00	1	0.00	194.00	194.00	1,181.25	6.09
24	2/19/04 11:30	2/20/04 8:30	2	0.00	206.50	206.50	1,968.00	9.53
25	2/21/04 12:00	2/22/04 22:30	2	0.00	305.75	305.75	3,999.00	13.08
26	2/23/04 20:00	2/24/04 22:00	2	0.00	231.75	231.75	3,396.00	14.65
27	2/27/04 18:00	2/29/04 23:30	3	0.00	190.25	190.25	2,838.50	14.92
28	3/4/04 17:30	3/5/04 9:00	2	0.00	72.00	72.00	566.00	7.86
29	3/14/04 21:00	3/15/04 9:00	2	0.00	53.50	53.50	642.00	12.00
		Totals	**75**	**1,244.00**	**13,524.00**	**14,768.00**	**124,810.00**	**8.45**

Water Year 2004 (October 1, 2003 – September 30, 2004) over the central Colorado Rocky Mountains started off significantly below the 1971-2000 average; the October 2003 precipitation was only around 40% of average. The cloud-seeding activities for the DW Program began on November 2, 2003. There were good opportunities for cloud-seeding activities during November, which was the only month during the DW Program's operational period when the target area precipitation was greater than the 1971-2000 average. December 2003 and early January 2004 had about average precipitation over the target area; this was followed by a 2-week dry spell in mid-January. February 2004 had good cloud-seeding opportunities, but the observed precipitation for this period was slightly below the long-term average. The first half of March 2004 only had two short cloud-seeding opportunities; the last cloud-seeding activity ended on March 15, 2004. Warmer than normal temperatures during March resulted in a decrease in snowpack snow water equivalent (SWE) and some snowmelt runoff at elevations below about 9,500-10,000 ft. MSL.

The precipitation trends described above for the first half of Water Year 2004 (October 2003 through March 2004) are evident in Figures 2.3 and 2.4. These figures show the precipitation and SWE trends for the Natural Resources Conservation Service (NRCS) SNOTEL sites at Summit Ranch (9,400 ft) and Fremont Pass (11,400 ft), respectively. Summit Ranch is located on the headwaters of the Blue River basin on the north side of the DW Program target area. Fremont Pass is located just outside of the west boundary of the target area. Overall, for the November 2003 through February 2004 period, the observed precipitation at the Summit Ranch and Fremont Pass SNOTEL sites were 98.9% and 87.3% of average, respectively.

The CWCB and DW determined that it was necessary to re-identify the generator sites not only for the research project, but also for clarity with past and future operational cloud seeding programs. Greg Bryant (Denver Water GIS Coordinator) and Joe Busto (CWCB) worked with Larry Hjermstad (WWC) to re-identify ice nuclei generator sites from initials of the generator operators to a letter-numbering system. The new site identification (ID) consists of a letter representing the project followed by a number (see Appendix 1). The result was an Excel spreadsheet that contains the site ID, location, elevation, status, and other information for all generator sites. This became the official identification system for DW and CWCB; the new seeding generator site ID scheme was built into the Colorado WDMP research project's GIS and graphics.

During the January 14, 2004 project conference call there was discussion about using the Generator Site Excel Spreadsheet for WWC seeding reports (e.g. dates, times, total hours, seeding rates, and primary target areas by site). Larry Hjermstad (WWC) suggested using one spreadsheet page per cloud-seeding opportunity event to reduce confusion. This was done and WWC went back to the start of the DW Program in November 2003 and put all cloud-seeding event reports into the same format. These event seeding report spreadsheets were combined into summary spreadsheets at the end of the DW 2003-2004 operational program.

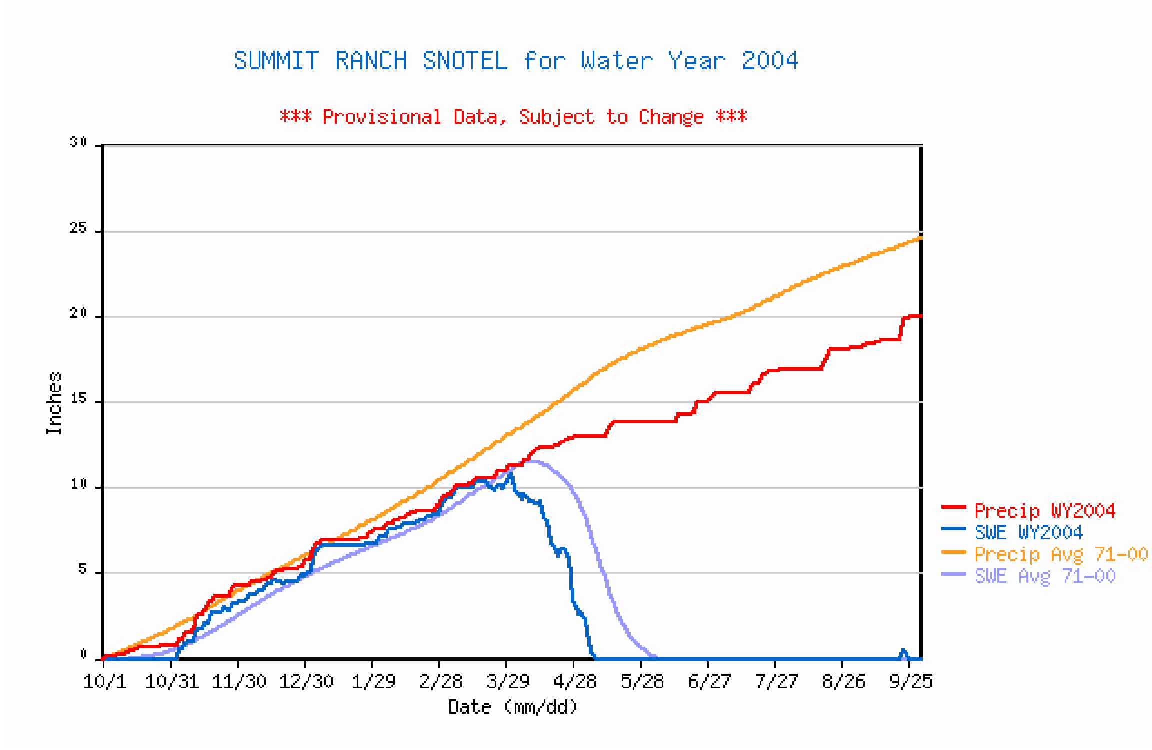


Figure 2.3. Summit Ranch SNOTEL traces for Water Year 2004.

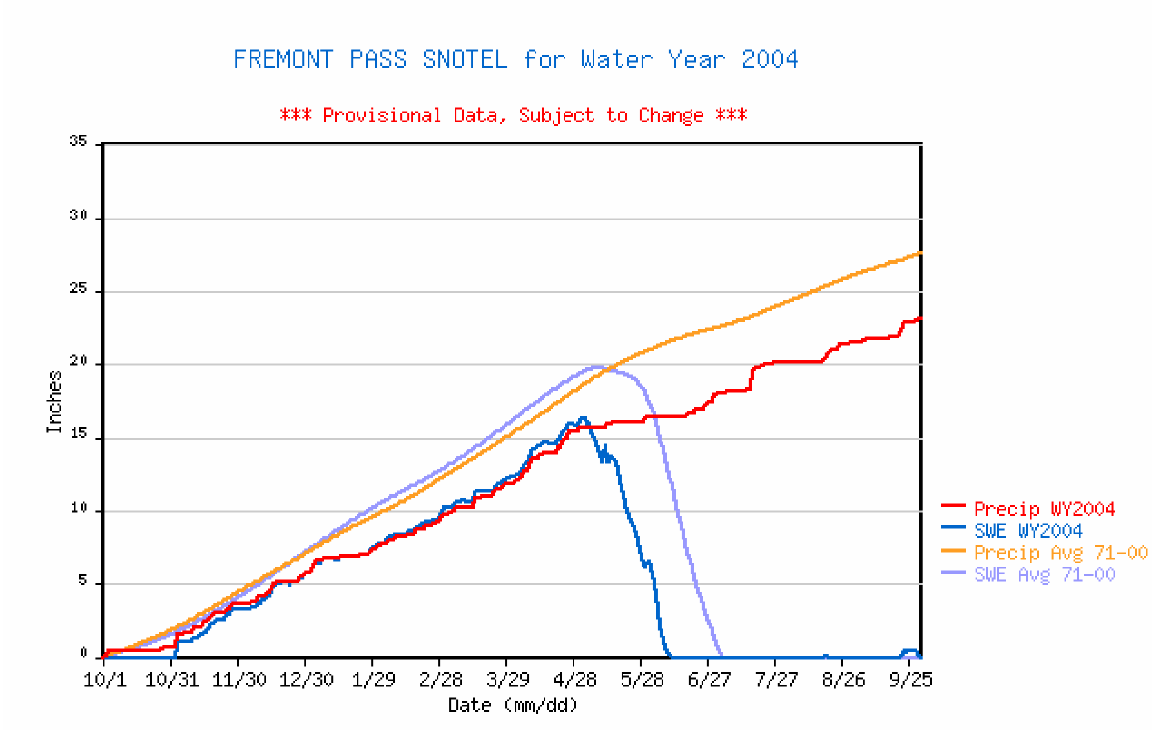


Figure 2.4. Fremont Pass SNOTEL traces for Water Year 2004.

2.3 CWCB–CSU Interagency Agreement

The WDMP-Colorado Financial Assistance Agreement was awarded to the CWCB on October 2, 2003. This original assistance agreement had a completion date of September 30, 2004, which did not agree with the proposal. The CWCB requested a no-cost time extension so that the WDMP assistance agreement would expire on December 31, 2004. In a letter dated December 2, 2003, Reclamation (Randy Jackson, Grants and Cooperative Agreements Officer) clarified that the period of performance would extend through to December 31, 2004 (this was later extended to September 15, 2005). Because of the delay in receiving this clarification from Reclamation, the Interagency Agreement between the CWCB and CSU was not signed until December 9, 2003. However, CSU team members did participate in the Project Kickoff Meeting at CSU on October 22, 2003 before the Interagency Agreement was signed. The Statement of Work in the CWCB-CSU Interagency Agreement listed six tasks and 16 related deliverables that were to be completed by the CSU research team. These tasks, which were included in the Colorado Proposal's Research Work Plan, are summarized in the following subsections of Section 2.

The Colorado WDMP research proposal to Reclamation and the CWCB-CSU Interagency Agreement included the purchase of a PC Cluster (1 master + 8 slave nodes, console and net switch) by CSU. These additional PC processors were needed to double the capacity of CSU's existing PC cluster to allow RAMS to be run daily for real-time project forecasts. CSU could not order the additional PC processors until after the CWCB-CSU contract for this project was in place. The new PC processors were ordered in late December 2003, received around mid-January 2004, and were installed during the last week of January. During installation, it was found that two out of the eight slave nodes had incompatible network cards (server adapters), and those two nodes could not be booted. The compatible replacement cards for the two nodes were subsequently received and installed. Full testing of the cluster took place during the second week of February 2004, and the RAMS real-time forecast runs were switched to the new cluster in mid-February.

2.4 Task 1 - Set up RAMS over the Denver Water operational cloud seeding areas and over the locations of the ground-based generators

One of the first tasks completed by the CSU team was to set up RAMS over the Denver Water operational winter orographic cloud seeding project area in the central Colorado Rocky Mountains. When the Colorado WDMP began, the CSU team found that they could enlarge Grid 3 and still get a 48-hr forecast completed reasonably fast. The new cluster funded by this project would allow a larger Grid 3. Their philosophy is bigger is better, because a larger grid provides forecast guidance for more users over a larger area.

CSU wanted to keep the Park Range in northwest Colorado within Grid 3, but needed to move the southern and eastern boundaries so that the target area for the project was more towards the center of Grid 3 and clearly away from the grid's boundaries. The RAMS 3-km fine grid domain as set up for the project was increased to 98 x 98 grid cells, and centered just to the northwest of Vail (VAI), Colorado. The total areal coverage of the enlarged Grid 3 was 294 km x 294 km (86,436 km^2); this Grid 3 is shown in Figure 2.5. The dashed line shows the target area boundary for Denver Water's 2003-2004 operational cloud seeding program. In addition to the grid and boundary, the map shows colored topography, towns (3-letter ID), ground-based seeding generator locations (△), SNOTEL (**X**), Snowcourse (**+**), and combined SNOTEL-Snowcourse (∗) sites.

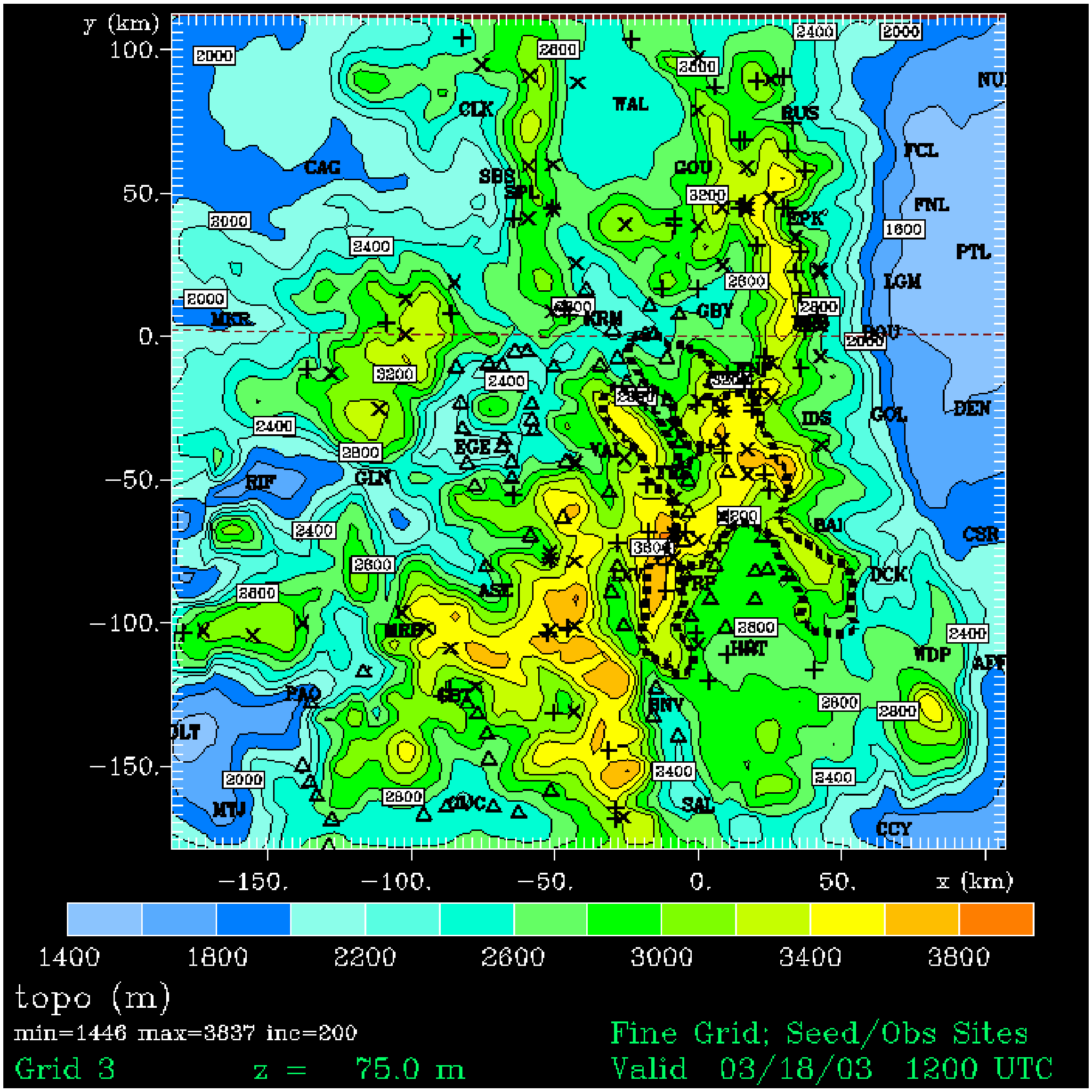


Figure 2.5. RAMS 3-km fine grid with Denver Water Program target area.

The northern boundary of Grid 3 as set up for the Colorado WDMP was along the Colorado/Wyoming border; the western boundary was positioned west of Grand Mesa and significant high terrain in west-central Colorado; the southern boundary was along the Gunnison and Arkansas Rivers; and the eastern boundary was well east of the foothills. These selected boundaries included all of the central Colorado Rockies (including Pikes Peak) while minimized crossing high mountain ranges, which was optimal for the model.

ESRI's ArcView 3-D Analyst was used by Ross Williams (GIS support contracted by CWCB) to create a 3-D model of the region immediately surrounding and including the DW Program's cloud-seeding target area. There remain questions among water managers and researchers about locating cloud-seeding generators in high mountain valleys and the effect of temperature inversions on the effectiveness of those particular stations. This 3-D model should help to display those generators that may not be as effective for seeding orographic clouds over the target area.

Three 3-D GIS topographic perspective views representing selected cloud-seeding wind regimes were prepared and included in this report. Figure 2.6 is a perspective view of the target area from the SW looking toward the NE. This is a good view for the S, SSW, SW to WSW wind regimes. Figure 2.7 is a perspective view of the target area from the W looking toward the E. This is a good view for WSW, W to WNW wind regimes. Figure 2.8 is a perspective view of the target area from the NW looking toward the SE. This is a good view for WNW, NW, NNW to N wind regimes. These three figures include the DW Program's target area boundary and the locations of WWC cloud-seeding generator sites.

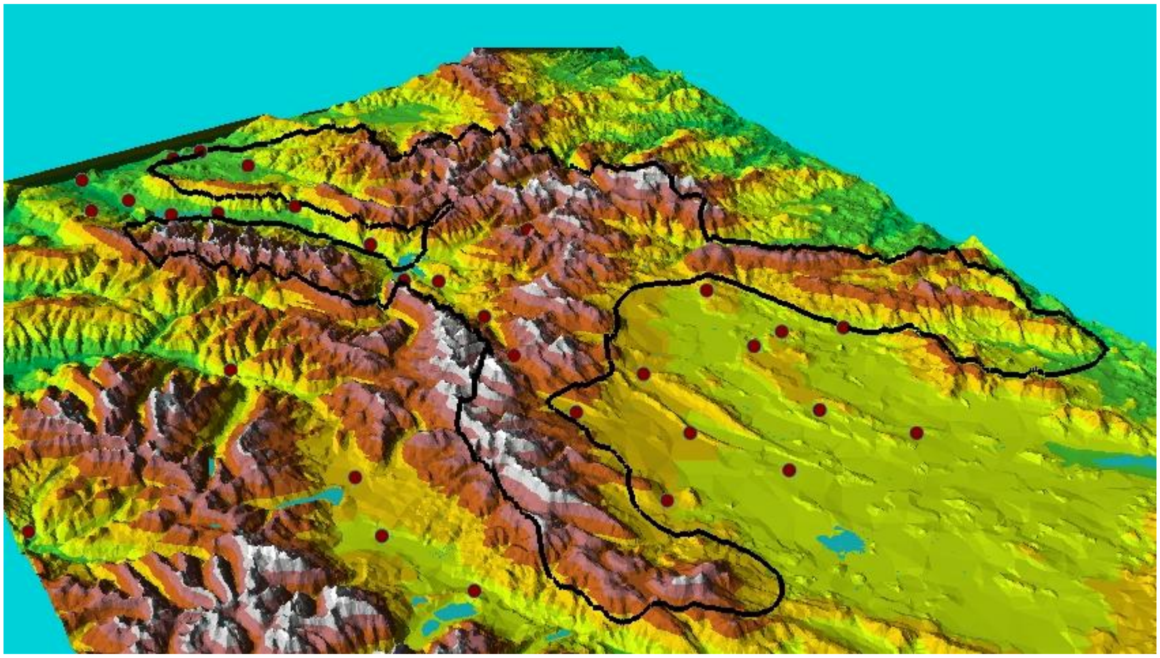


Figure 2.6. SW to NE Topographic Perspective View

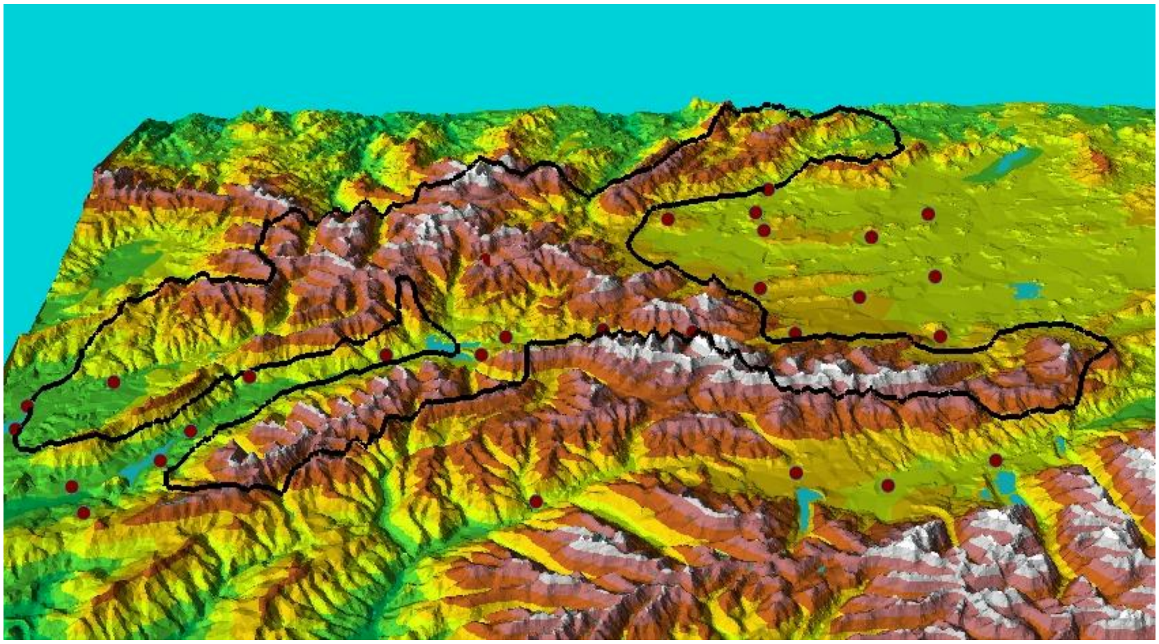


Figure 2.7. W to E Topographic Perspective View

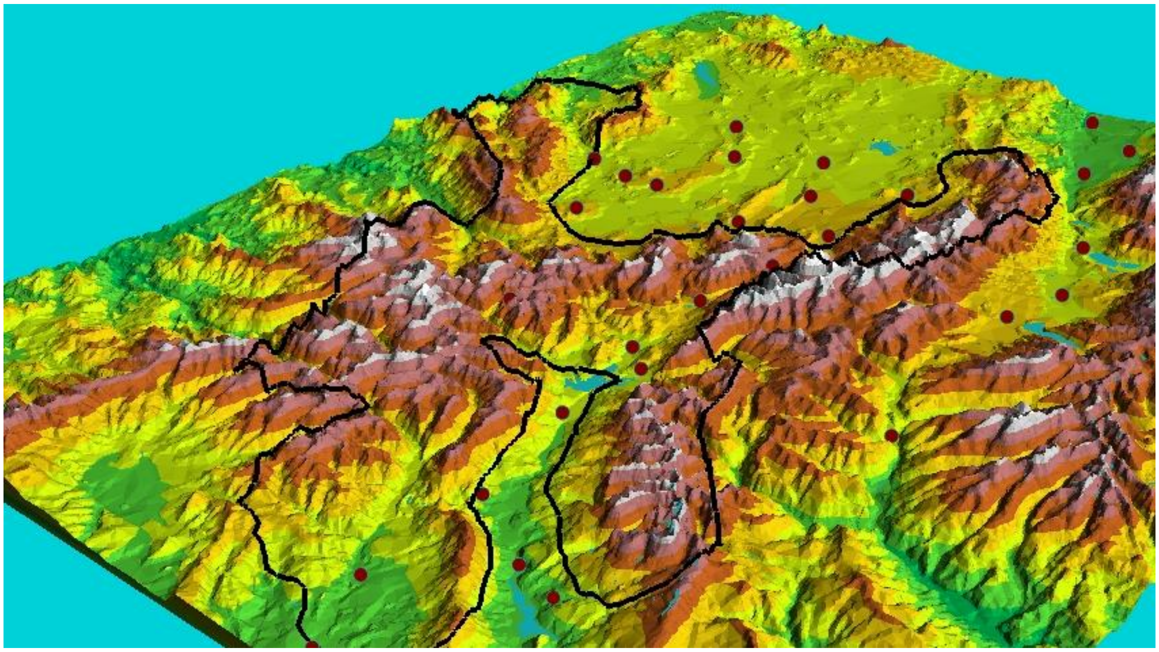


Figure 2.8. NW to SE Topographic Perspective View

2.5 Task 2 - Implement algorithms simulating cloud seeding generators as sources of IFN at specified ground-based sites

The CSU RAMS was used to provide real-time forecast support during portions of the DW 2003-2004 Program's winter orographic cloud-seeding activities. The model physics explicitly represent orographic clouds and precipitation processes in mixed-phase clouds. A two-moment microphysics scheme was used, in which mixing ratios and concentrations are predicted for seven hydrometeor categories. Through the course of the 2003-2004 winter season, evaluation of the model's real-time forecast performance led to a series of adjustments in the simulation design.

The model was extended to include seeding effects in order to evaluate the no-seed vs. seed precipitation simulated by RAMS. Algorithms were added to RAMS simulating sources of IFN from cloud-seeding generators (low-level model grid points). The extended model simulated sources of silver iodide (AgI) released at each generator as recorded in WWC's operational cloud-seeding logs. The AgI was treated as a second predictive IFN field with its own activation characteristics. The AgI activation law was based on laboratory experiments that used the same types of generators and AgI materials as used by WWC on the DW Program. (WWC used a 4% AgI solution with sodium iodide as a carrier in acetone along with 1% moth balls to improve nuclei activation between –2.5°C and –8.0°C.) As with the standard IFN category, the number of seeded IFN that is activated becomes a source of pristine ice crystals in equal numbers and a corresponding sink of IFN that is available for subsequent activation.

The RAMS seeding simulations were set up identically as the control runs, except for the additional IFN category and the seeded AgI. Simulated 24-hr precipitation in the seeded runs replaced the amounts from the corresponding non-seeded control runs to form complete daily, event, monthly and seasonal simulated precipitation totals that include all cloud-seeding operations.

The CSU Team originally intended to use a seeding event selected from the DW 2002-2003 Program's operational season as a test case for the RAMS model seeding code, in order to develop the code and have it ready when the DW 2003-2004 Program's cloud-seeding data became available. DW Program seeding contractor Larry Hjermstad (WWC) chose the February 4, 2003 seeding event for this test case and provided the seeding data. However, several factors delayed the test case experiment, including the delayed acquisition of the computer cluster, uncertainties in generator identification and location for the previous season, and shifted priority to current season cases as those seeding data became available. Thus this test case study was not completed until early May 2004, where it was used as one of the seeding sensitivity studies for Task 4 in the research project. The primary sensitivity explored with this test case involved reducing the initial background or natural IFN concentration to 40% of that used in the standard code, for both control and seeding runs. The February 4, 2003 seeding test case summary is in Appendix 3.

2.6 Task 3 - Perform simulations of Lagrangian transport of seeding materials on selected days covering a range of wind and stability regimes

This task first involved selecting certain meteorological regimes that impact the transport and dispersion of AgI cloud-seeding material, and then identify six case study days that represent those regimes. The selection of case study days was based primarily on observed wind direction, low-level stability, and the location and amount of snowfall. The CSU Team then performed Lagrangian trajectory analyses using RAMS model output data to examine the predicted trajectories and the extent to which they interact with clouds in the target area. Findings from these case studies are summarized in Subsection 3.8.

The selection of meteorological regimes included the identification of precipitation observation sites. The research project team decided that the NRCS SNOTEL (SNOpack TELemetry) network would provide the bulk of precipitation data that would be used in project studies. This was due to the network's reasonably large number of stations at representative higher elevation sites over the entire study area, the reliability and generally high quality of its 24-hr precipitation and SWE reports, and its uniform 0800 UTC (0100 MST) reporting time. The 0100 MST observation time is convenient for evaluating RAMS 24-hr simulated precipitation.

There were 94 SNOTEL sites within the state of Colorado, but only 63 of these sites were on RAMS Grid 3. Appendix 2 gives location/ID information for all 94 sites; the appendix figure shows the site locations within RAMS Grid 3. Two of the 63 sites on Grid 3 had obviously bad data and were not used in project studies. The SNOTEL sites used for statistical evaluations included 12 located within the target area and 18 non-target area sites. These 30 SNOTEL sites are hilited with yellow in Appendix 2. The locations of SNOTEL sites within and near the DW Program target area are shown in Figure 2.9. The numbers identifying the sites correspond to SNOTEL site information listed in Appendix 2.

SNOTEL sites located to the west and southwest of the DW and Vail/BC cloud-seeding operations may have been affected by other seeding programs (see Figure 1.2); therefore, they were only used for the overall assessment of the model's simulated precipitation across the Grid-3 domain. For the detailed evaluation of control no-seed vs. seed simulations, the CSU team used the 30 sites indicated by yellow hilite in Appendix 2 plus 31 other non-target area sites within Grid 3 (61 total). The final selection of sites included in the statistical evaluation was done after quality control of the SNOTEL precipitation and SWE data, aided by comparison with data collected by NWS climate stations, ski areas, Community Collaborative Rain, Hail & Snow (CoCoRaHS) sites, and NRCS snowcourse sites.

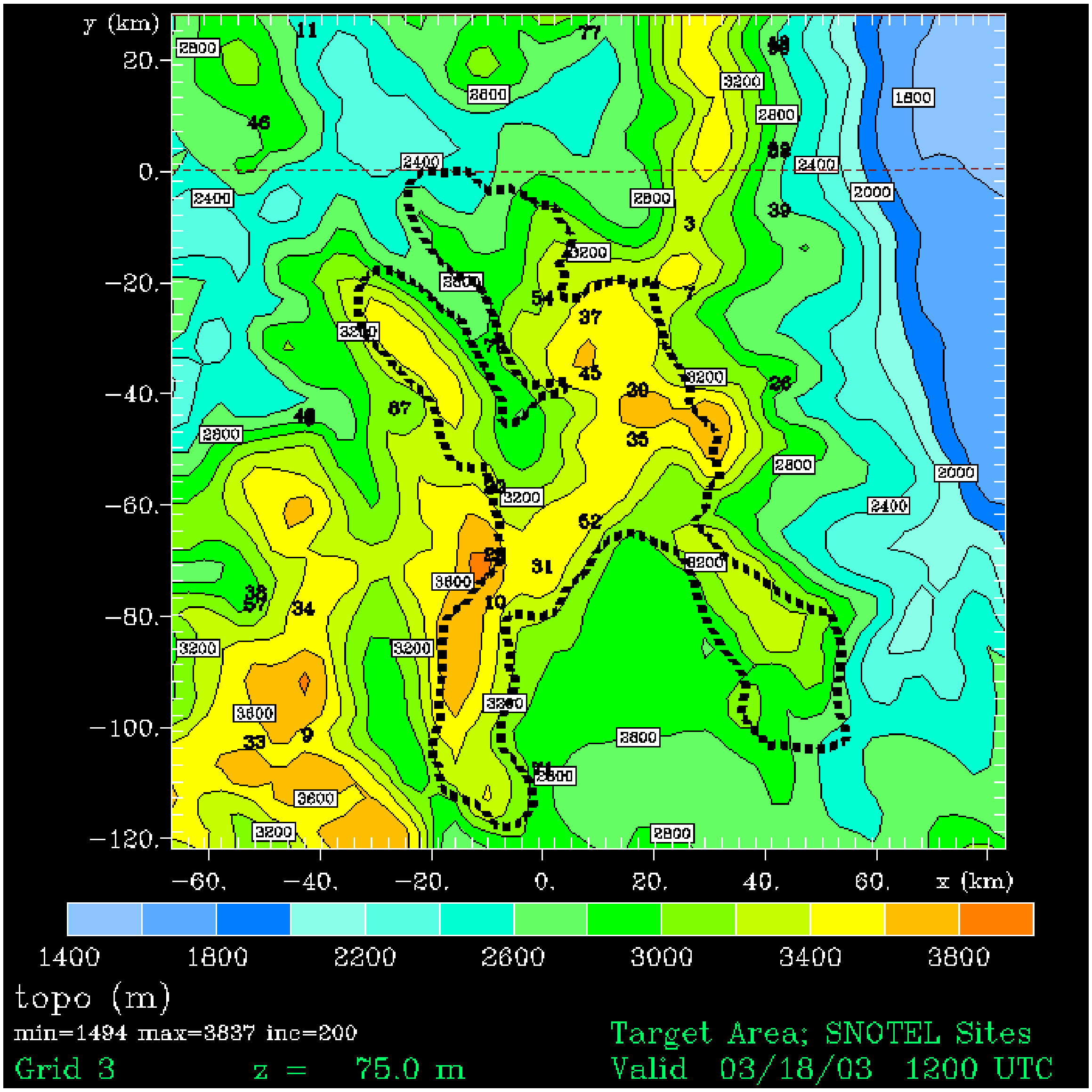


Figure 2.9. SNOTEL sites in and near the DW Program target area.

The DW 2003-2004 Program conducted cloud-seeding operations during 29 winter orographic weather system events. The start and stop times for the seeding events are listed in Table 2.1. These events were comprised of all or portions of 75 calendar days. Some of the 75 days had limited hours of cloud seeding activity. On some days the cloud-seeding activities began during the evening. On other days, the WWC manual generators may have been turned on early (i.e., in the evening before the operators went to bed), or were turned off late (i.e., in the morning after the operators got up). Larry Hjermstad (WWC), coordinated with Ray McAnelly from the CSU team to select the best 30 cloud-seeding "Days" for use in the post-season research evaluations. These 30 Days are listed in Table 2.2. The "Day" used for evaluation was from 0800 UTC (0100 MST) of the given Day to 0800 UTC (0100 MST) of Day+1. This period matches with the 24-hr SNOTEL precipitation and SWE observations with the date of Day+1. This "Day" also corresponds to the period from which the 24-hr model simulated precipitation is derived, viz. from the 8-hr forecast to the 32-hr forecast in a given RAMS simulation initialized at 0000 UTC with Eta data.

Table 2.2. List of 30 Cloud-Seeding Days Selected for Evaluation
(Prev – seeding was continued from previous 24-hour calendar day)

No.	Date	Seeding Time	Targeting Wind	Meteor. Regime
*1	Nov 3, 2003	All 24 hrs	215 – 240 deg	Best SSW
2	Nov 5, 2003	1100-0100 hrs	230 – 250 deg	Good SW
3	Nov 7, 2003	0830-0100 hrs	230 – 240 deg	Good SW
4	Nov 10, 2003	0730-0100 hrs	250 – 260 deg	Best WSW
5	Nov 11, 2003	All 24 hrs	260 – 290 deg	Best WNW
*6	Nov 14, 2003	All 24 hrs	240 – 270 deg	Best WSW
7	Nov 17, 2003	All 24 hrs	270 – 305 deg	Best WNW
8	Nov 18, 2003	Prev-1100 hrs	305 – 330 deg	Good NW
9	Nov 22, 2003	0800-0100 hrs	230 – 305 deg	Fair Tropa
10	Nov 25, 2003	1000-0100 hrs	260 – 275 deg	Good W
*11	Nov 26, 2003	All 24 hrs	275 – 325 deg	Best WNW
12	Nov 27, 2003	Prev-1300 hrs	330 – 350 deg	Good NNW
13	Dec 8, 2003	All 24 hrs	220 – 360 deg	Best Tropa
14	Dec 13, 2003	1000-0100 hrs	300 - 305 deg	Good WNW
*15	Dec 15, 2003	Prev-2300	340 – 360 deg	Best NNW
16	Dec 21, 2003	0800-0100 hrs	245 – 290 deg	Good Tropa
17	Dec 26, 2003	All 24 hrs	210 – 260 deg	Good Tropa
18	Dec 27, 2003	All 24 hrs	260 – 310 deg	Fair Tropa
19	Dec 30, 2003	All 24 hrs	270 – 230 deg	Best WSW – trof apch
*20	Jan 2, 2004	All 24 hrs	250 – 265 deg	Best WSW
21	Jan 3, 2004	All 24 hrs	260 – 265 deg	Best WSW
22	Jan 28, 2004	0800-0100 hrs	265 – 285 deg	Good W
23	Jan 29, 2004	Prev-2100 hrs	285 – 300 deg	Fair WNW
24	Jan 31, 2004	All 24 hrs	260 – 350 deg	Fair Tropa
25	Feb 4, 2004	All 24 hrs	310 – 350 deg	Best NNW – Low SE
*26	Feb 5, 2004	All 24 hrs	350 – 360 deg	Best NNW
27	Feb 8, 2004	All 24 hrs	190 – 340 deg	Good Tropa – Low SE
28	Feb 22, 2004	Prev-2200	220 – 175 deg	Best SSW – trof apch
29	Feb 24, 2004	Prev-2200	175 – 240 deg	Best SSW – trof NE
30	Feb 29, 2004	Prev-2200	335 – 350 deg	Best NNW

*Selected as Case Study Day for Lagrangian particle transport study.

Table 2.2 shows that there were eight meteorological regimes identified as candidates for the Lagrangian particle dispersion and transport study. These eight regimes and the number of days in each are listed in Table 2.3. The six Days selected for the Lagrangian study analyses are identified by an asterisk (*)

before the day number in Table 2.2 and listed in Table 2.3. The six Lagrangian case studies were identifies as “best” cases in four meteorological regimes.

Table 2.3. Regimes identified for 30 Selected Days and Lagrangian analyses.

Meteorological Regime	No. of Days	Lagrangian Analyses
SSW wind	3	1 case study day
SW wind	2	0
WSW wind	5	2 case study days
W wind	2	0
WNW wind	5	1 case study day
NW Wind	1	0
NNW wind	5	2 case study days
Tropa or Low	7	0

2.7 Task 4 - Perform forecasts for seeded and non-seeded days

CSU implemented a Web site for the Colorado WDMP starting around mid-December 2003. The URL is: http://rams.atmos.colostate.edu/clseeding/. The main menu on the project Web site included links to the following pages:

- Real-time Forecast (no-seed model runs based on 0000 UTC Eta data)
- Networks (towns, seeding generators, precipitation observation sites)
- Daily Precipitation Maps (simulated 24-hr precipitation fields, time series)
- Data (SNOTEL & Snowcourse Snow Water Equivalent 24-hr precipitation)
- Evaluation & Studies (simulated seeding, particle transport, statistical)
- GIS Maps (particle concentration and simulated precipitation)
- Progress Reports (required quarterly technical progress reports)
- Meetings & Conference Calls (summaries - Colorado WDMP related)
- Conferences & Workshops (Colorado WDMP related)
- Related Publications

The CSU Web site for the Colorado WDMP was a dynamic site in the sense that it was updated and enhanced throughout the research project. This Web site should be active for some time after the project final report is submitted, so that readers can access considerably more information than what can be summarized or appended to this report. One good example of this is the link to “Daily Precipitation Maps” that allows viewing of project area 24-hr simulated no-seed and seed precipitation maps, and time series graphs of seeding-related parameters from November 2003 through March 2004. The “Real-time Forecast” link allows access to current RAMS forecasts for Colorado.

Real-time RAMS forecast simulations were run once daily to support the DW 2003-2004 Program’s cloud seeding operations. Numerous map and graphical forecast products at 2-hr intervals through the 48-hr forecast period were posted on the CSU Web site and available via the Internet to assist WWC in the seeding operations. There were many forecast products related to the high temporal and spatial resolution development and evolution of orographic clouds, cloud base, temperatures in the lower cloud layer, and wind flow to above the barrier crest. When available, these parameters were used by WWC to help determine which generators would be utilized, when they would be activated, and at what rate the AgI nuclei would be generated. Figures 2.10 through 2.13 are examples of RAMS Grid 3 0000 UTC Forecast Run products; many such products were available to WWC for cloud seeding decision-making.

Figure 2.10 shows the wind flow and temperature at the 700-mb level (this height is about 10,000 ft msl, which is near the mountain tops in Colorado). In addition to the 2-hr forecasts, there is a neat animation feature that allows the user to watch the wind flow and temperature fields change over time. (See CSU WEB site – Real-time Forecast link.) Each full barb on a wind flag represents a wind speed of 10 knots; a half barb represents 5 knots.

Figure 2.11 shows the surface wind flow and accumulated total precipitation in millimeters (liquid) as related to the target area. Again, the animation feature provides estimates on the timing of precipitation within the target area, as well as the location and amount.

Figure 2.12 shows a west to east cross-section through the target area along 39.6 degrees N latitude. The figure includes the topography, temperatures above the terrain in 5°C intervals, relative humidity (%) pattern, and the W-E (u) component of the wind flow. The highest relative humidity concentrations (indication of moist air) are on the upwind side of the mountain peaks. The animation feature allows the user to easily view forecast changes over time in the relative humidity and temperature aloft out to 48 hours.

Figure 2.13 shows a north to south cross-section through the target area along –106.0 W longitude. The figure includes the topography, temperatures above the terrain in 5°C intervals, vertical motion or velocity (w), and the N-S (v) component of the wind flow. The areas of positive (upward) vertical motion just above the terrain would be the likely areas for cloud and perhaps precipitation development. The animation feature allows the user to easily view forecast changes over time in the vertical motion and temperature aloft out to 48 hours.

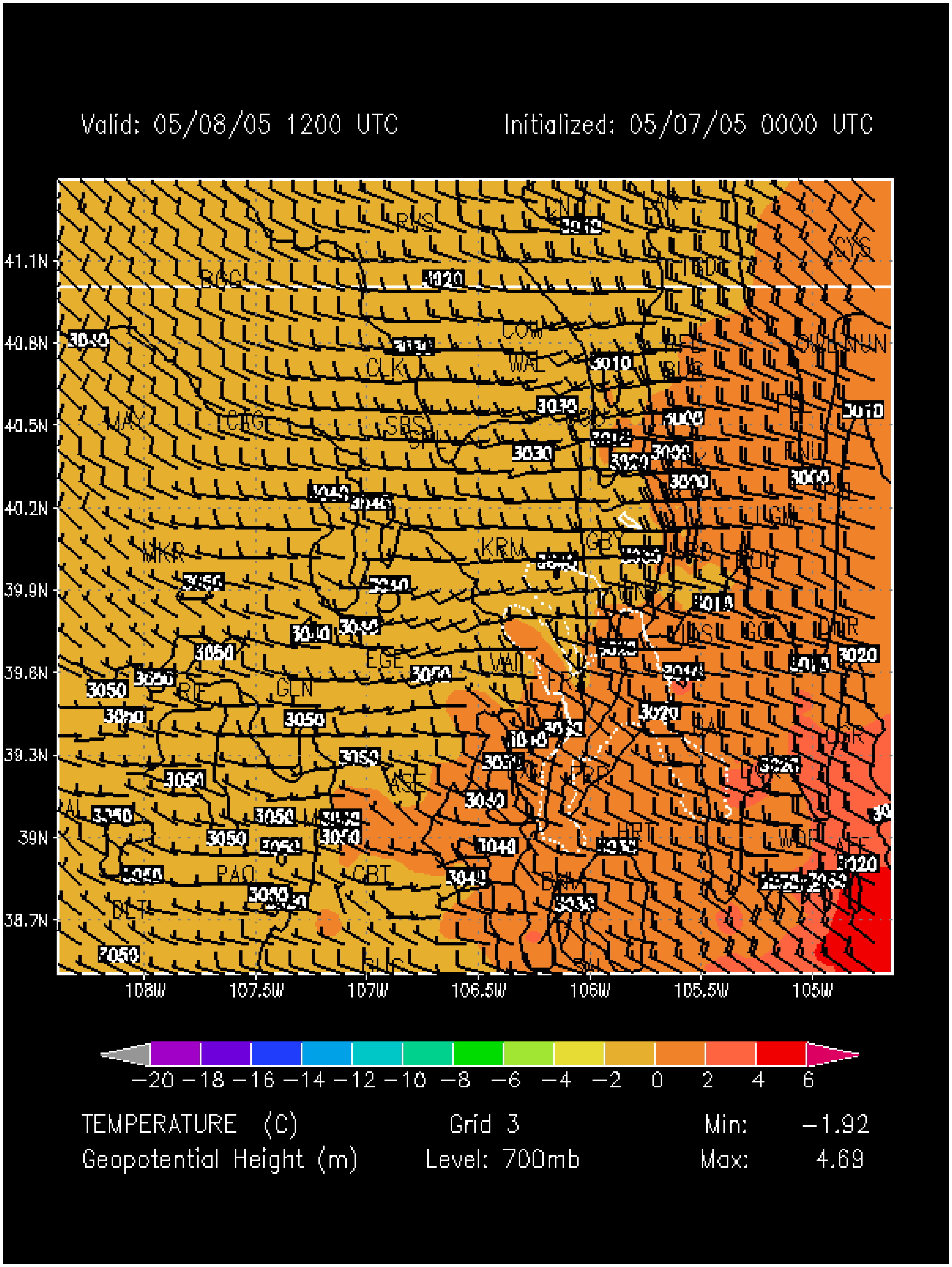


Figure 2.10. Example of RAMS 700 mb forecasts of wind flow and temperature.

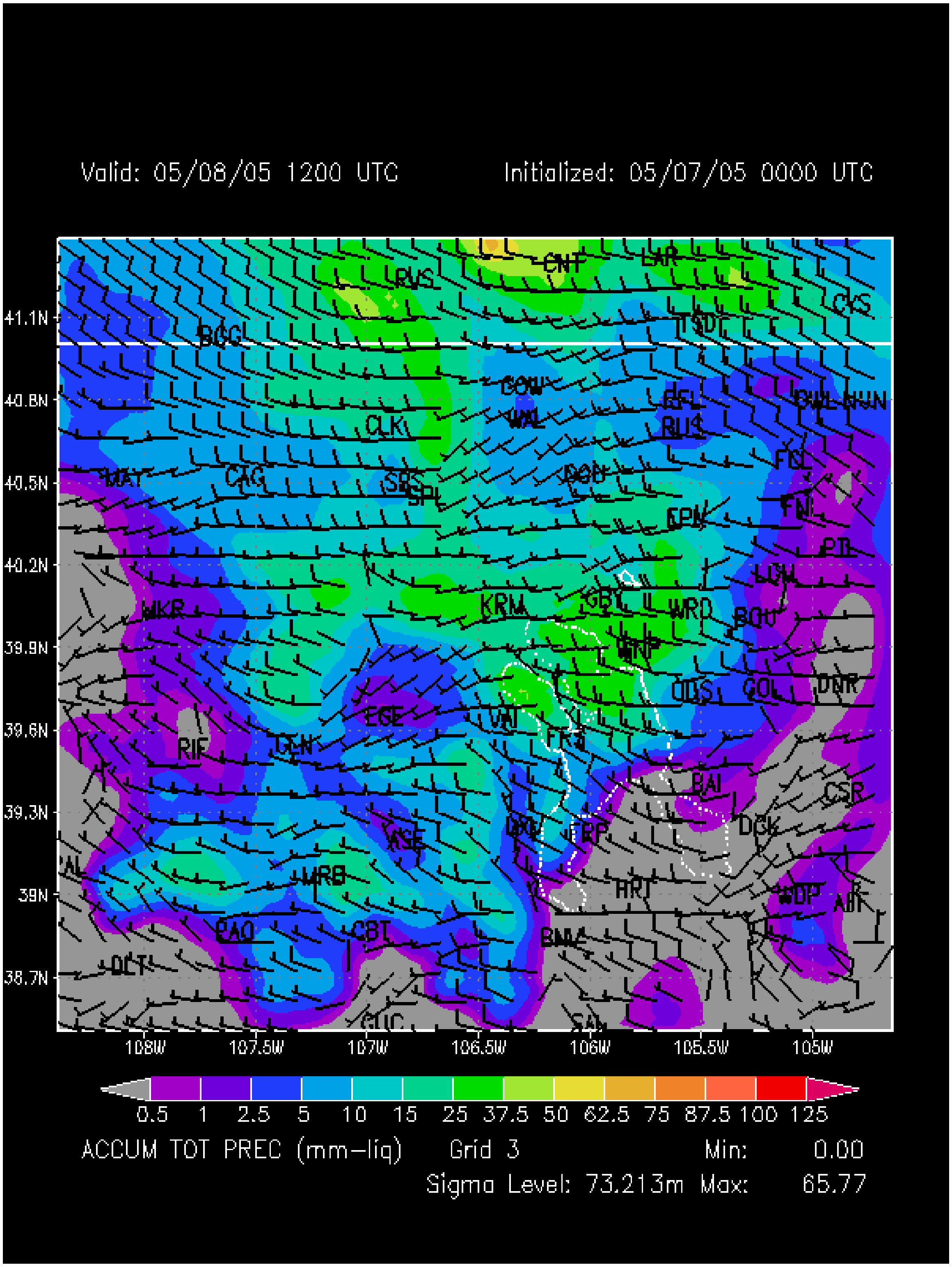


Figure 2.11. Example of surface wind flow and accumulated total precipitation.

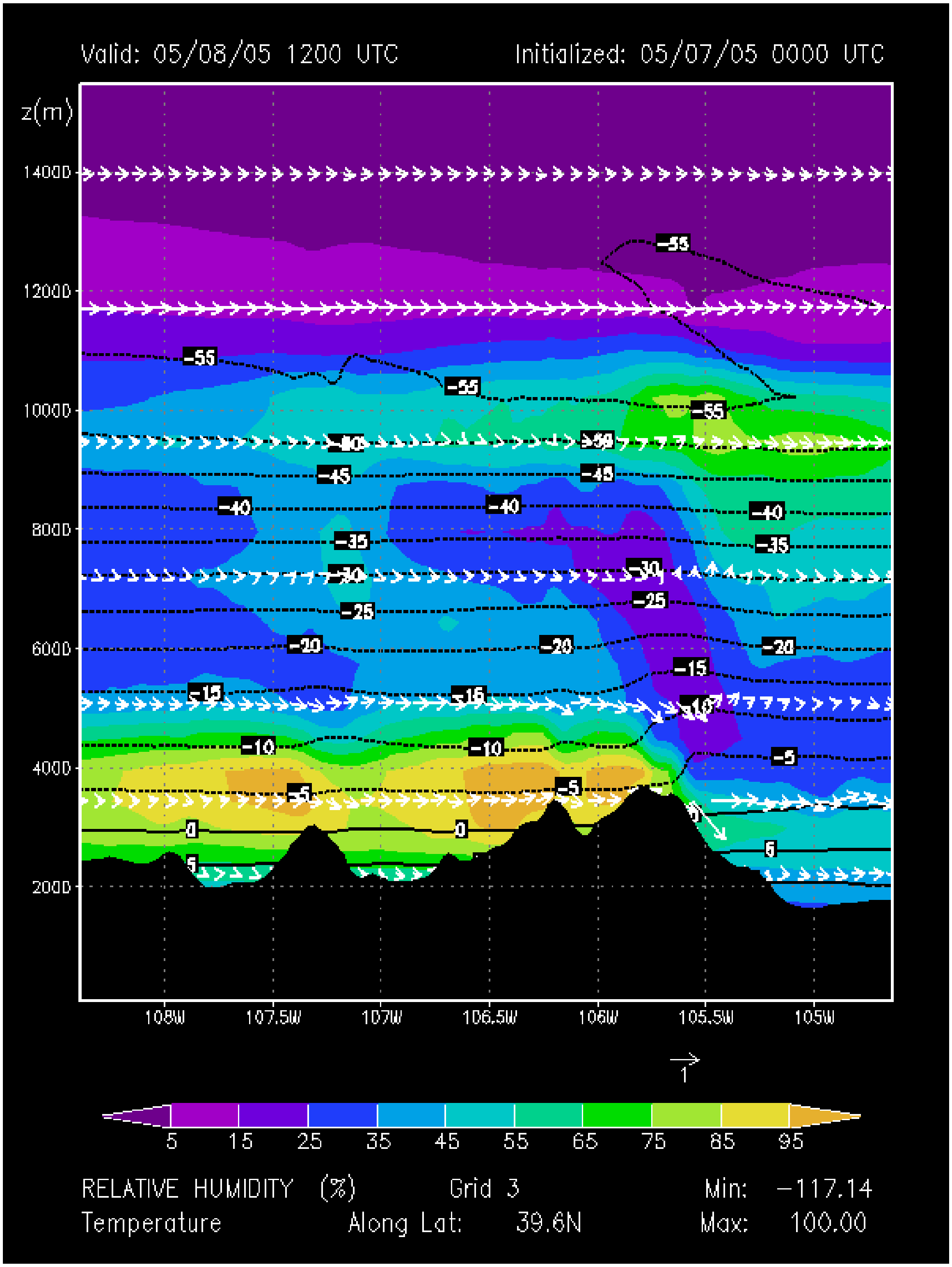


Figure 2.12. Example of a west to east cross-section through target area.

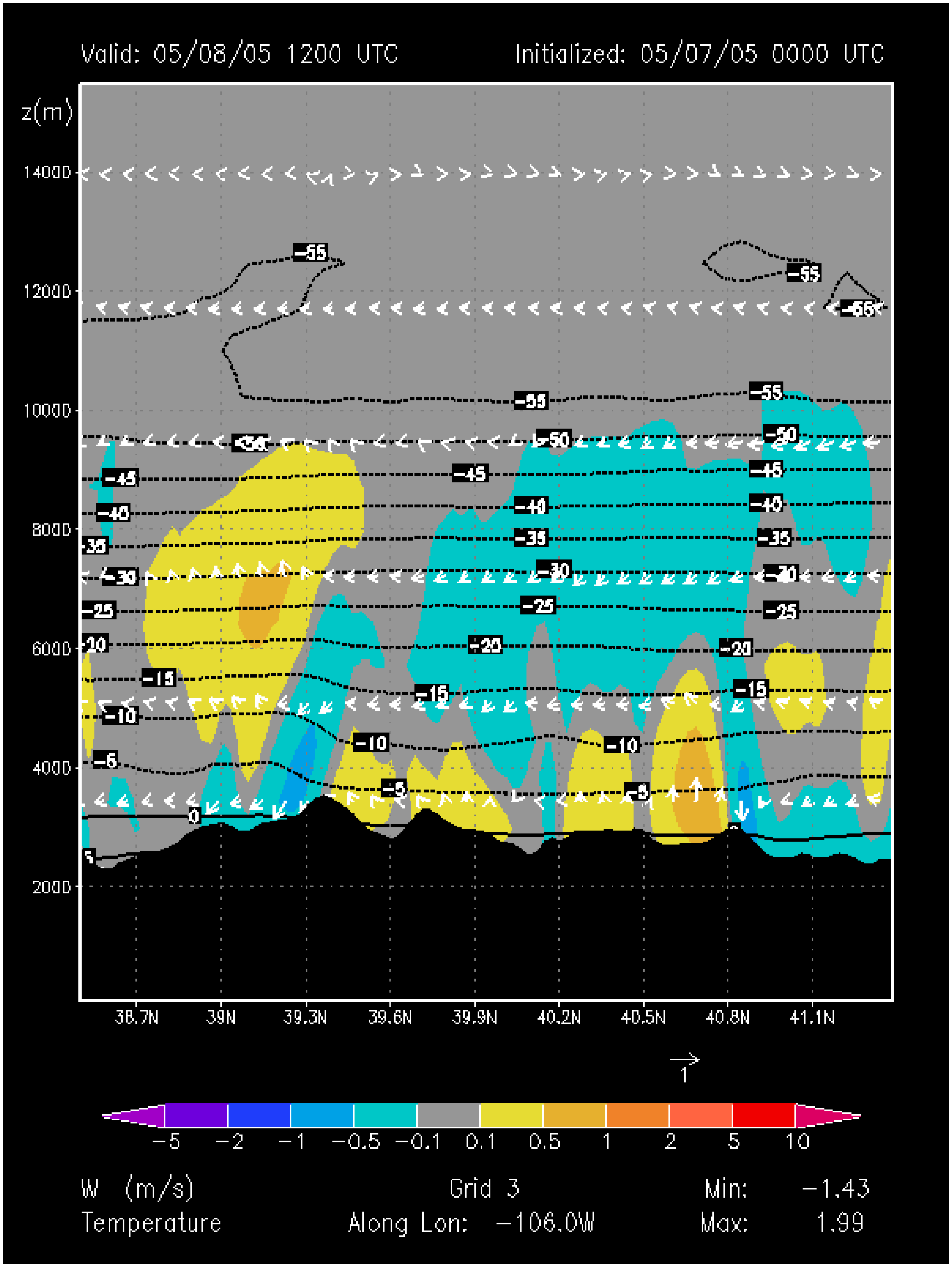
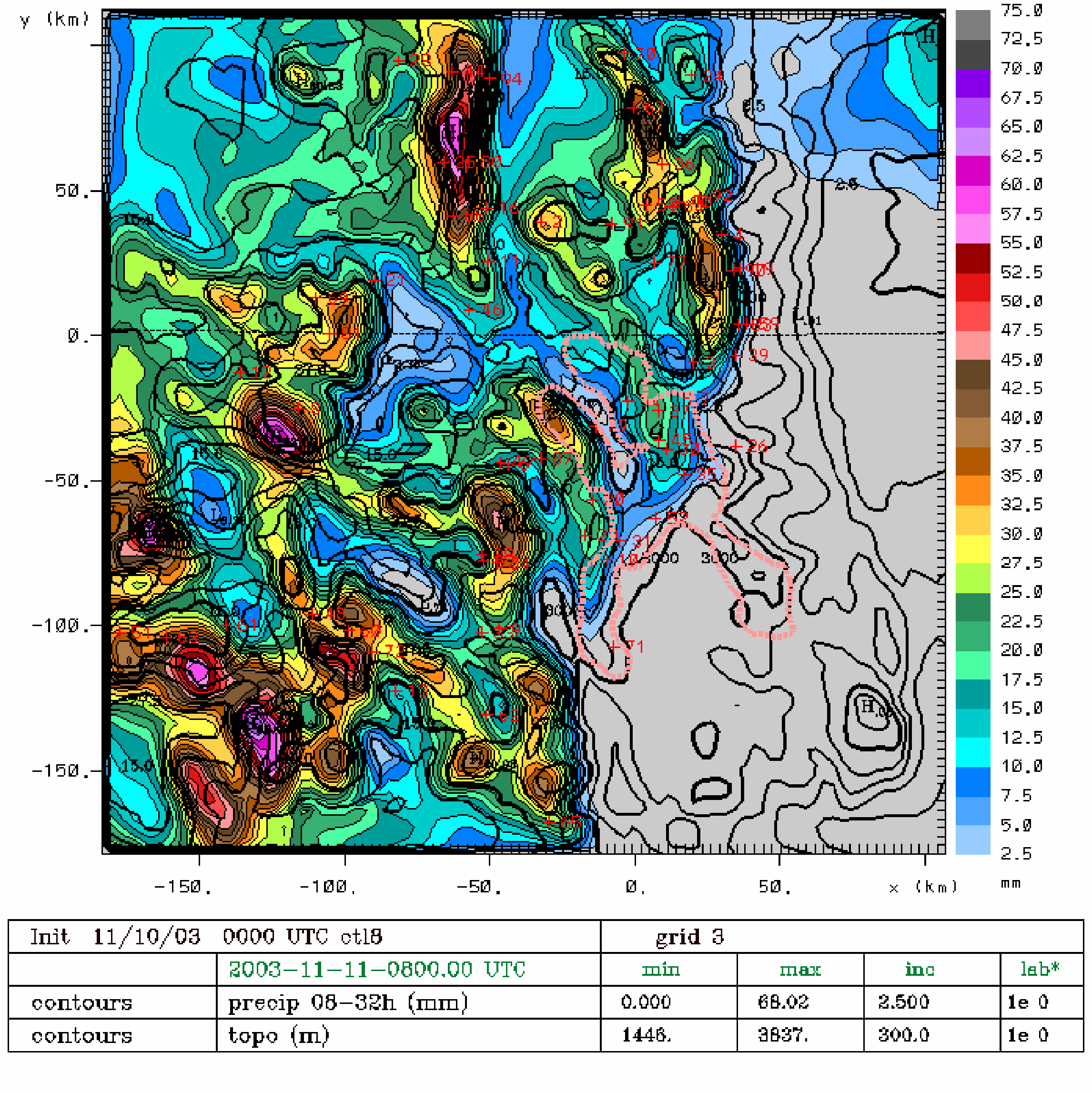


Figure 2.13. Example of a north to south cross-section through target area.

The products generated by CSU for the project's Web site are created using NCAR Graphics code that is distributed as part of the overall RAMS package. This package analyzes data directly on the RAMS grid, without any interpolation necessary (unless the analysis is on a constant pressure surface, in which case there is vertical interpolation). On the precipitation maps the inward pointing tick marks indicate the center of each 3 x 3-km grid cell. This method uses the actual grid-point data, which allows an analyst to zoom in and look at exactly what the model values are at a specific point, making troubleshooting easier. The RAMS Real-time forecast graphics are generated using the GrADS graphics package, which is in widespread use by lots of modelers (RAMS and otherwise) because of its open sourcing and ease of using. With this package, the RAMS data are horizontally interpolated to a latitude-longitude grid with about the same resolution as the 3-km data. The area plotted on a GrADS Grid 3 map is a little smaller than the actual RAMS Grid 3 domain (because of differences between the RAMS Polar-Stereographic mapping and the GrADS latitude-longitude mapping). But for all practical purposes, the resultant fields are the same regardless of which package is used.

The difference between the 24-hr simulated precipitation accumulations from the NCAR Graphics and GrADS graphics packages is visually noticeable. Figure 2.11 was generated using Grads. The precipitation accumulation is for the 8-hr to 32-hr forecast period ending November 11, 2003 at 0800 UTC (0100 MST). Figure 2.14 is the simulated precipitation accumulation for the same 24-hr period generated after-the-fact by using NCAR graphics.

At the time the WDMP Colorado Financial Assistance Agreement was awarded (October 2003), it was expected that the existing CSU RAMS PC Cluster would be available for daily model non-seeded forecast runs until the new PC processors were procured and the cluster expanded. However, due to delay in finalizing the CWCB-CSU Interagency Agreement for the research project (not signed until December 9, 2003), CSU was not able to purchase the new PC processors on the schedule they had anticipated. Consequently, starting the evening of December 1, 2003, CSU switched the real-time 0000 UTC RAMS forecast cycle from their faster cluster to a slower one. This change was due to impending deadlines of two other research projects where the use of the faster cluster was critical; i.e., they required the greater memory and processing speed of the faster cluster. The model-forecast products still got to the CSU Web site, but at a 3-times slower rate than usual. (The slower forecast run took 12 to 14 hours of computer time to finish.) The model-forecast output was still archived on the CSU project Web site as usual.



Init 11/10/03 0000 UTC ctl8		grid 3			
	2003-11-11-0800.00 UTC	min	max	inc	lab*
contours	precip 08-32h (mm)	0.000	68.02	2.500	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 2.14. 24-hr simulated precipitation ending Nov. 11, 2003, 0800 UTC. This figure was generated by CSU using NCAR Graphics. Compare this figure with Figure 2.11 that was generated by using the GrADS graphics package.

The other two CSU projects that required the faster system ended in early January 2004, and the RAMS 0000 UTC real-time forecast runs were switched back to the faster cluster effective the evening of January 10, 2004. So beginning January 10, 2004, through the transition to the new cluster, and on through the end of the DW 2003-2004 Program's cloud-seeding operations, the real-time forecasts were run on a fast cluster that should have provided timely support for the seeding operations. The new cycle forecast was completed around 0200 MST.

An operational problem that arose with the slower real-time forecast runs also applied, but to a lesser extent, with the faster runs. When a new forecast cycle began, the existing procedure had been that all of the old products from the previous cycle were deleted from the CSU Real-time Forecast Web site. This was to avoid confusion by users, who otherwise might not realize that when they were examining a time sequence of products, the valid time might cross over discontinuously from the new forecast cycle to the old cycle. (The model run produces 2-hr forecasts out to 48 hours. The new 2-hr forecasts are posted right after the 0000 UTC model run completes them.) However, particularly with the slow runs, the deletion of the old cycle products resulted in no high-resolution forecast guidance for the first day or so of the new cycle, until the new cycle reached that far.

It was thus decided to keep the old forecast cycle's products until they were superceded and over-written by each two-hourly increment of the new cycle. In this way, the products valid at 36 hours in the old cycle (or 1200 UTC on Day 2), for instance, were retained to provide guidance at 1200 UTC on Day 1 of the new cycle, until the new cycle's products were produced. To help the user avoid the possible confusion of not realizing the discontinuity, prominent labels were updated and displayed on each menu that give the initialization time of the current cycle and how far out in the 48-hr cycle it has reached. Thus, any products beyond that point were more easily recognized as being from the older cycle, but were still available for high-resolution guidance. This change was made beginning with the January 19, 2004 forecast cycle.

The real-time RAMS 0000 UTC forecast runs, originally intended to constitute the set of control (no-seed) runs for the entire season, were determined to be unusable for that purpose due to several problems that became evident deep into the cold season. The problems were traced to three factors, two of which involved overly warm soil temperatures that resulted in too much surface sensible heat flux and low-level warming. One problem was a soil initialization scheme that prevented the soil temperature from initializing colder than 0°C and the soil moisture from being initialized in frozen form, when those conditions should have been allowed at high elevations deep into winter. The second problem was a coding error with the thermal energy content applied to soil, where sub-freezing soil improperly warmed rapidly to 0°C when the slightest initial frost or frozen precipitation occurred in the topmost soil layer.

The third problem was the use of an alternate horizontal diffusion scheme that CSU had used in previous winter seasons in order to avoid runaway cooling at the lowest layer that sometimes occurred with the standard diffusion scheme. The alternate scheme was not strictly mass conserving, however, and in many runs it apparently resulted in too much mass and moisture convergence into the high country.

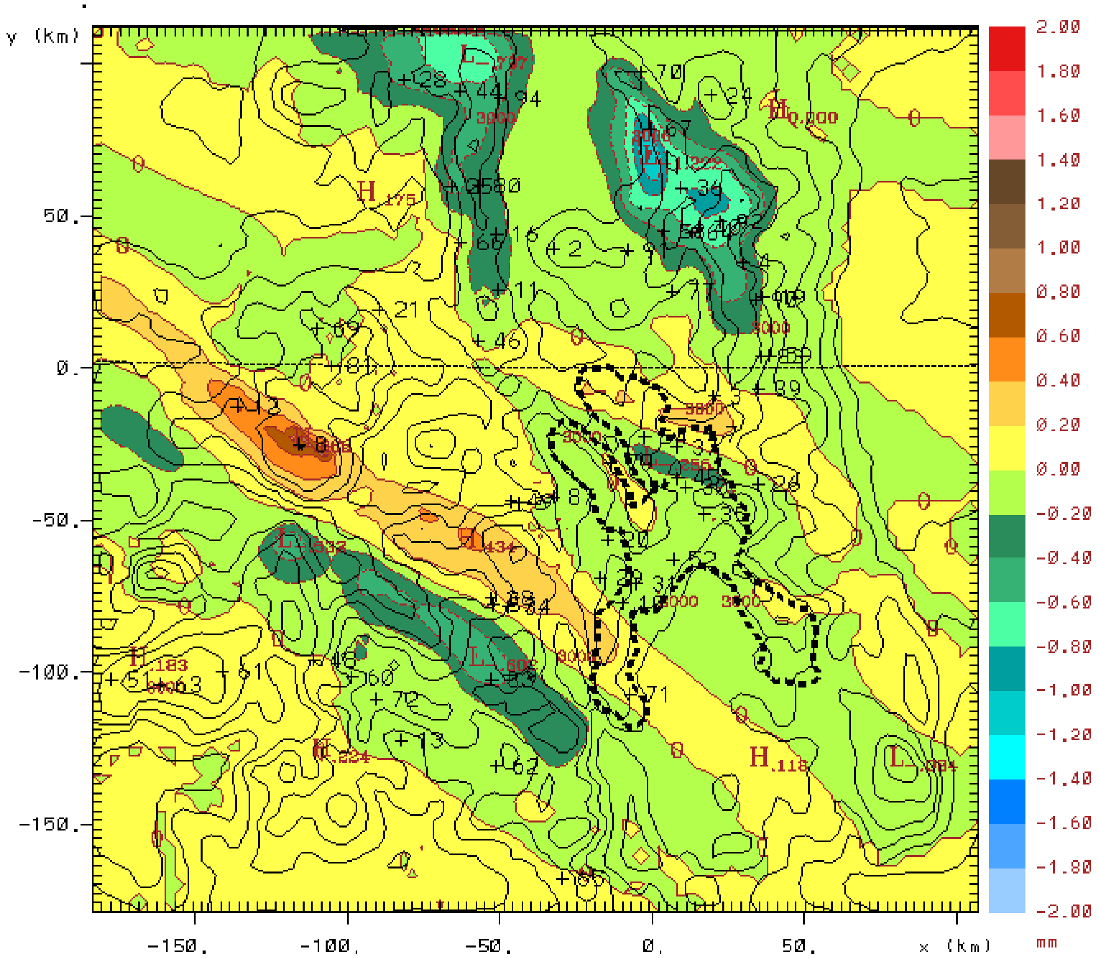
These three problems resulted in unrealistically warm low-level (basically below ridge crest) temperatures and overestimates of precipitation in the mountains. These problems became noticeable about mid-January and persisted into February 2004. The problems were basically solved through making the following changes: allowing the initialization of frozen soil moisture at sub-freezing temperatures; fixing the coding error in the thermal energy content formulation for soil; and switching back to the standard mass-conserving and horizontal-diffusion scheme. These changes were combined with a doubling of the low-level vertical grid spacing (delta-z in the model) that generally prevents the runaway cooling that occurs frequently using that scheme with the original 150 m vertical grid spacing. For the February 14, 2004 real-time model forecast run (still a pretty cold regime), delta-z was increased to 300 m. A test showed that this change lessened, but did not eliminate, the excessive cooling problem; there was still unreasonable surface cooling in the February 14 real-time run. After February 14, there were no additional changes made to the real-time forecast model; all three fixes were operative, with a delta-z of 300 m. Even after the model fixes were implemented on February 14, there still remained a low-level warm temperature bias and a simulated precipitation over prediction bias.

2.8 Post-operational RAMS Control and Seeding Runs

After the model fixes were implemented in mid-February 2004, the real-time model forecasts improved significantly. However, as CSU began experimenting with the model seeding runs, it became evident that even the improved real-time forecasts were unusable as control no-seed runs. This was because the model code that was developed to simulate seeding effects through a second IFN category was substantially different from the model code used for the real-time forecasts, with inconsistencies in microphysical options that made evaluation of subtle seed/no-seed effects difficult. Due to these inconsistencies and the earlier problems described previously, it was determined that after-the-fact control no-seed as well as seed model runs would have to be performed for the entire DW 2003-2004 Program's operational period (November 2003 through March 2004). This was necessary in order to get completely consistent pairs of control/seed runs, which differed only due to the introduction of AgI and its activation in seeding runs.

The initial sets of control no-seed and seed runs indicated unexpected seeding effects. There were very small differences in simulated precipitation fields. More unexpectedly, the patterns of the difference fields on some of the days were generally organized into positive and negative bands aligned more or less with the mean wind and extending across much of the 3-km fine grid, far upwind and laterally from the target area. Figure 2.15 shows an example of such a seed – control simulated precipitation difference analysis. The targeting wind for this seeding event was 275 to 325 degrees. In this figure, the + signs followed by numbers are locations of SNOTEL sites. The difference scale along the right side of the figure provides for a maximum value of 2.00 mm (0.08 in), but the maximum 24-hr difference indicated in the figure is only about

0.80 mm (0.03 in). The findings from the simulated seed vs. control no-seed precipitation analyses are summarized in Subsection 3.3.



Init 11/26/03 0000 UTC z sd8		grid 3			
	2003-11-27-0800.00 UTC	min	max	inc	lab*
contours	sd-ctl precip 08-32h (mm)	-1.222	0.8662	0.2000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 2.15. Example of Seed–Control simulated precipitation difference analysis.

To further investigate the unexpected simulated seed vs. no-seed precipitation sensitivities before beginning the full set of control and seed production runs, a series of sensitivity tests were performed. These tests involved one or more of the following: the background IFN concentration; constant background IFN concentration fields vs. initial concentrations that could evolve through advection and diffusion; the number of IFN released per gram of AgI burned; several rates of AgI activation based on a range of empirically derived possibilities; and the inclusion of a second cloud water mode, which along with the standard mode provided a bimodal cloud water size distribution. These experiments all produced similar results regarding the small sensitivity to seeding on precipitation amounts and the large-area manifestation of these slight differences. In mid-May 2004, after settling on a more suitable set of microphysical options based on these sensitivity tests, CSU began the full production of control no-seed and seed runs.

After finishing the control no-seed and seed runs for the 30 selected days (Table 2.1) and proceeding on through another dozen seeding days, another problem was discovered. The winds used to initialize the RAMS model and to provide time-dependent lateral boundary conditions on the largest grid (Grid 1) are derived from NCEP's Eta model initialization and 3-hr forecast files. In the Eta files, the u and v wind components are relative to the Lambert-conformal mapping of the Eta grid, rather than being true u and v wind components. The model code used for the real-time runs had been adapted long ago to properly transform the Eta winds onto the RAMS grid. However, RAMS source code that was used to extend the model to include seeding effects had never been adapted to properly transform the Eta winds

The improperly transformed winds were small in error and practically unnoticeable, except perhaps in the northern corners of the large Grid 1 domain where they can deviate from their true direction by as much as 30-degrees and thus be highly non-geostrophic. When this inadvertent error was discovered in early July 2004, several cases were rerun with the corrected winds in order to assess the sensitivity to the error. The effects of the incorrect winds on simulated precipitation amounts were trivial to moderate on the 3-km fine grid in the individual cases, but tended to produce more precipitation due to slightly incorrect large-scale dynamics being forced into the western boundary of the large grid. Because there is a simulated precipitation over-prediction bias in the model (discussed in Section 4), it was decided to rerun all the control no-seed and seed runs using the corrected wind transformation in order to eliminate this systematic error that exacerbated the problem. The final production seed runs were completed on 24 August, and the final control runs (including all non-seeded days) were completed on 9 September 2004.

2.9 Task 5 - Perform evaluations of model predictions of precipitation using Multivariate Randomized Block Permutation

Model skill for simulated precipitation was evaluated using the 30 days selected for use in project evaluations (Table 2.1). This evaluation used Multivariate Randomized Block Permutation (MRBP) statistics (Mielke, 1984, 1991) as implemented by Cotton et al. (1994) and Gaudet and Cotton (1998). SNOTEL 24-hr precipitation and SWE data were used for the evaluations (SNOTEL sites used are identified in Appendix 2). The purpose for this evaluation was to determine if the model-forecast skill was sufficient to say something definitive about seed vs. no-seed simulated precipitation differences, or if these differences were within the noise level or level of uncertainty of the model.

This task was comprised of two parts, viz. setting up the MRBP code for the evaluation, and then using the adapted code for the MRBP analysis. Results of the MRBP evaluation of model performance are summarized in Subsection 3.7.

Dr. Paul Mielke provided a copy of the MRBP Analysis Code. His original code was translated from FORTRAN77 to FORTRAN90 (a more widely used version) and modified for the project by Dr. Gustavo Carrió. However, the modified program strictly follows Mielke's methodology. The updated version of MRBP consisted of two codes (note - this brief summary does not intend to describe the methodology associated with the MRBP analysis that is explained in detail in Mielke et al., 2001):

INPUT.f90: This code reads observational and simulated precipitation fields for a series of stations. These input files (obse.dat, reglr.dat, and seed.dat) are written in a free format matrix with rows and columns corresponding to days and stations, respectively. The number of stations (N_STAT) and the number of days to be considered in the test (N_DAYS) are input parameters. The code generates input matrices in the format needed by the MRBP analysis for RAMS standard simulations and for seeded runs (rglr_mrbp.in and seed_mrbp.in, respectively). These files consist of a series of blocks corresponding to different test conditions. An example of the format of each block of the file that INPUT.f90 would generate for three stations and four days is given as a comment at the beginning of MRBP.f90. Each block is preceded by a line that tests conditions.

MRBP.f90: This code computes the test statistic and associated P-value of a randomized block experiment. The program performs repeated MRBP analysis in one operation considering different input parameters such as alignment within blocks, distance function commensuration and rank tests (see Mielke, 2001). While running the program, it gives the user the option to compare the observation vs. the regular simulations or observation vs. the seeded runs and automatically selects the corresponding input matrix. The outputs for the comparison of the observation vs. the non-seeded and seeded runs are written in two text files: seed_mrbp.out and rglr_mrbp.out, respectively. The agreement measure, P-value, as well as the value of delta, its expected value, the variance and skewness are given for all above-mentioned options. This code performs repeated MRBP analysis in one operation considering different test conditions and therefore the corresponding results are also written in each output file.

2.10 Task 6 - Research study supervision and reports

The grant agreement from Reclamation for the Colorado WDMP required three quarterly technical progress reports, a mid-project meeting between Reclamation research staff and the Colorado WDMP Project Team, a presentation on the overall project after project research studies and evaluations had been essentially completed, and a final report.

The three technical progress reports were completed on schedule and submitted to Reclamation by Joe Busto, CWCB. These progress reports were posted on the CSU project Web site under the Progress Reports link on the Menu.

The mid-project meeting was held while DW's 2003-2004 Program's cloud-seeding activities were still in progress. Colorado State University, Department of Atmospheric Science hosted the meeting on February 19, 2004. The discussions included a review of problems that might impact the ability to complete the work tasks on the schedule proposed, and what was being done to overcome such problems. By February 19 CSU had made necessary fixes to the RAMS Real-time Forecast run, which allowed the CSU Team to demonstrate the operational model to others attending the meeting. It was emphasized that the research project would not provide a definitive evaluation of the Denver Water operational program's seeding activities. RAMS was being enhanced to simulate cloud seeding and, therefore, was expected to provide indications for cloud seeding effects and the types of meteorological conditions favorable for winter orographic cloud seeding. A summary of this meeting is posted on the CSU project Web site under the Meetings & Conference Calls link on the Menu.

The American Meteorological Society (AMS) and the Weather Modification Association (WMA) hosted the 16th Conference on Planned and Inadvertent Weather Modification as part of the AMS 85th Annual Meeting, January 9-13, 2005, San Diego, California. A special session on the Reclamation WDMP was planned for the 16th Conference on Weather Modification. Steve Hunter from Reclamation requested that all state WDMP research projects make a 20-minute presentation during this special session. This presentation would fulfill the requirement in the grant agreement from Reclamation for the Colorado WDMP. Mr. Curt Hartzell, CWCB/DW Technical consultant, prepared and gave a Power Point presentation on the Colorado WDMP. This presentation is posted on the CSU project Web site under the Conferences & Workshops link on the Menu.

3. RESULTS AND FINDINGS

3.1 Use of RAMS Real-time Forecast Output for Cloud Seeding Activities

One of the objectives of the Colorado WDMP was for the DW Program's cloud seeding contractor, Western Weather Consultants, LLC (WWC), to use the model output from RAMS Real-time Forecast runs in their operational forecasts. The model was to be run once daily in support of cloud-seeding operations. The model was initialized with 0000 UTC (1700 MST) Eta model 3-hr forecast analysis fields and run for a period of 48 hours. As stated in Subsection 1.6, when run on CSU's fastest PC cluster, a 48-hr forecast run typically begins at 0300 UTC (2000 MST) when the 0000 UTC Eta forecast data are available. The complete RAMS Real-time Forecast run is usually available by 0900 UTC (0200 MST). The output from these forecast runs was posted on the CSU project Web site for use by WWC.

Since the AgI nuclei generators used by WWC were manually operated, the late availability of the RAMS forecast products was a problem, because of WWC's policy of not calling their generator operators after 2200 MST. Thus if a number of calls had to be made, the operational decisions for the night had to be made by 2100 MST. The timing problem was made worse because CSU had to start the project making the RAMS Real-time Forecast run on an older PC cluster that was about 3-times slower than normal (reference Subsection 2.7 Task 4).

CSU was able to switch to their faster PC cluster on January 10, 2004 before the PC cluster that had been procured for project use was installed, tested, and operational. This switch was possible because the other two CSU projects that required the faster system ended in early January. However, as stated in Subsection 2.7, the existing procedure was that when a new forecast cycle began, all of the old products from the previous cycle were deleted from the CSU Web site. On January 19, a change was implemented that kept the old forecast cycle's products until they were superceded and over-written by each new 2-hr forecast increment.

After CSU began using the faster PC cluster for the 0000 UTC real-time forecast run, the 2-hr forecast beginning at 0800 UTC (0100 MST, the start of the 24-hr precipitation period) was usually available by 2100 MST. So beginning in mid-January, WWC was able to view these new cycle forecasts before finalizing their operational decisions for the following 12-hr period. Larry Hjermstad (WWC) began making daily operation notes on his decision making and on his use of RAMS. These daily notes for January 15 – February 29, 2004 are in Appendix 4. Larry's daily attempt to use the RAMS real-time forecasts led to the discovery of several model problems (reference Subsection 2.7 Task 4). The final model fixes for the project were in place starting with the February 14 real-time run. Unfortunately, this was after most of the DW Program ended on February 10, 2004 (reference Subsection 2.2).

When available, WWC used the CSU RAMS forecast outputs in conjunction with other meteorological services provided on the Internet. The forecast products were evaluated to define favorable seeding conditions within cloud systems over the seeding target areas in the central Colorado Rocky Mountains. The procedure that WWC used to refine the opportunity recognition of favorable cloud conditions using the CSU RAMS forecast output was as follows:

1. Using the RAMS Grid 3 surface map, WWC determined the most likely timing of the start and ending of the precipitation event using the 2-hr precipitation presentation. This presentation also gave a fine detail of surface wind direction and speed. This information helped to confirm the best network of generators to use and also the favorable continuity of the wind transport of the seeding material on 2-hr presentations. This was very important if there was any concern for the development of possible surface inversions.

2. The RAMS 2-hr precipitation rate presentations were used to determine when precipitation was expected to start in various parts of the target areas and also to determine when the greatest amount of precipitation would occur in determining the “best: seeding periods. Such periods would also coincide with favorable wind flows and favorable cloud-base temperatures.

3. Review the total precipitable condensate regions and the vertical velocity fields on the 700 mb level (about 10,000 ft msl) presentations throughout the duration of a weather event. In particular, these forecast products were used to determine where the condensate would occur. This information along with the fine detail wind field gave a good representation of precipitation regions expected in the target areas and confirmed the most targetable areas for seeding from the existing meteorological conditions and available generators. The negative vertical velocity fields in association with light or drainage wind fields can signal possible developing inversions which would disrupt the favorable dispersion of seeding material.

4. Along with the above information, WWC looked at various vertical cross-sections across the target region (both W-E & N-S) to evaluate temperature and wind profiles, and the likely location of the cloud base and its change with time throughout the target area. They also looked at the quantity and location of the cloud development relative to the barrier (used the vertical motion profiles) to interpret its seedability given the current dispersion conditions. WWC would also check to see if the model had any significant concentration of ice particles (IFN) in the lower region of the cloud system when the cloud-base temperatures began to turn cold (colder than –10°C).

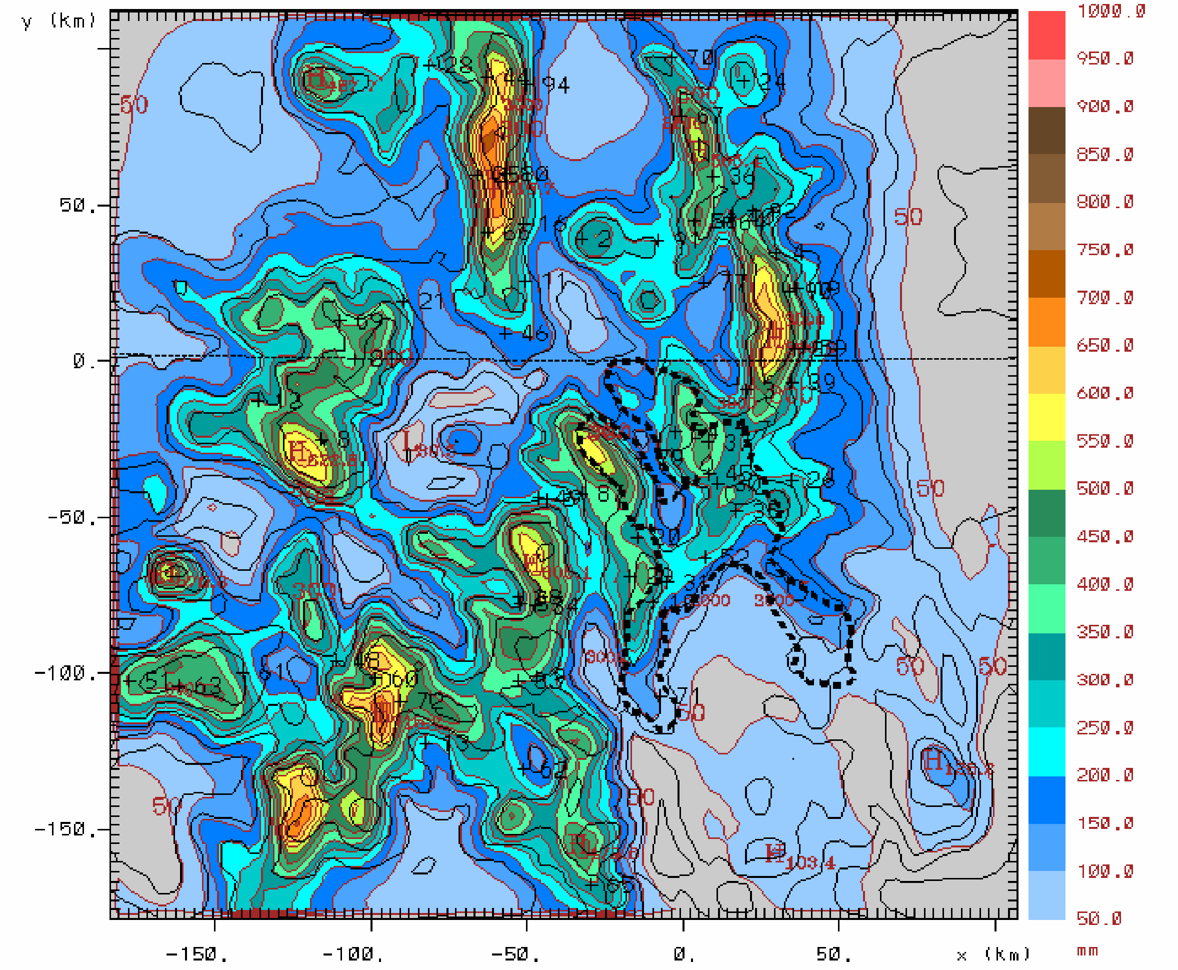
WWC found that after the model fixes had been implemented in mid-February 2004 and the RAMS was real-time forecast 0000 UTC cycle was run on the new PC cluster, the forecast output that was posted on the Web site was very useful. The low-level warm temperature problem had been greatly reduced and the model provided timely input for operational cloud seeding decision making. There were numerous forecast products and parameters to evaluate. In addition to the 2-hr forecast presentations, the animated forecast loops provided a quick visual picture of changes over time.

3.2 Comparison of Model Control Precipitation and SNOTEL Observations

An evaluation of the model control run precipitation was based on the 30 selected cloud-seeding days identified in Table 2.2 (in Subsection 2.6). These 30 control run simulations were a subset of the full winter season set of 152 daily post-operational control simulations described in Subsection 2.8. The 30 days were selected from the 4-month 1 November 2003 through 29 February 2004 period. As discussed in Subsection 2.6, each run was initialized at 0000 UTC of the date of the selected day, and the daily 24-hr precipitation period was from 0800 UTC (0100 MST) of that day to 0800 UTC the following day (hours 8 to 32 of the simulation).

Figure 3.1 is the 30-day total control run precipitation field on Grid 3, i.e. the sum of the individual simulated 24-hr precipitation fields over all 30 days selected for evaluation. The distribution has a strong elevational dependence, ranging from less than 50 mm (as low as no precipitation) in lower elevations, to a maximum of 718.7 mm (28.3 in) near the crest of the Park Range in the north-central portion of Grid 3. The greatest accumulation within the target area was about 600 mm (23.6 in). The major mountain ranges generally have several hundred millimeters at their higher elevations, with the major exception being the lower local maximum over Pikes Peak in the southeastern portion of Grid 3. This pattern is qualitatively similar to that shown on a map of Colorado Average Annual Precipitation 1951-1980, produced by the Colorado Climate Center (Doesken et al. 1984).

The wind regimes for the 30 selected days are representative of winter climatology over the central Colorado Rocky Mountains. The similarity between the model simulated precipitation pattern for the 30 days (Figure 3.1) and the annual average precipitation pattern (Doesken et al. 1984) suggests that the model control runs reliably produced the general distribution of wintertime precipitation with its strong topographic dependence. However, it should be kept in mind that the 30 days are from a 4-month period (November-February) whereas the annual pattern represents a 12-month period. Also, the 30 days represent mainly orographic precipitation with some imbedded convective precipitation, while the annual pattern includes all precipitation events and over twice as much total precipitation (see Figure 2.3 & Figure 2.4).



Select 30seed-day Ctl8 Pcp		grid 3			
	2004-03-01-0800.00 UTC	min	max	inc	lab*
contours	season precip (mm)	0.000	718.7	50.00	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 3.1. 30-day total control run RAMS Grid 3 simulated precipitation field (The 30 days are from the 1 November 2003 through 29 February 2004 period.)

Observed precipitation data used for evaluation of the control run simulated precipitation were obtained from the NRCS SNOTEL sites on Grid 3, as discussed in Subsection 2.6. SNOTEL data were obtained from the NRCS website in two forms: (1) tables of daily cumulative gage-measured precipitation for the water year, and (2) for total snow water equivalent (SWE) as measured by the SNOTEL snow-pillow sensor. Both sensors were updated daily with automated telemetric reports valid at 0800 UTC (0100 MST), and both to the nearest 0.1 inch (2.54 mm) resolution. Complete winter season precipitation and SWE tables were obtained for each SNOTEL site. The 24-hr precipitation and SWE increments were calculated by daily differences in the cumulative precipitation and total SWE, respectively. Negative increments (which may be real due to evaporation and/or wind-blown loss of snow off the pillow sensor) were assumed to represent zero 24-hr increments for analysis purposes.

Quality control of the daily SNOTEL data consisted of three steps: (1) plotting daily increments of precipitation and SWE for each of the 30 selected days for each SNOTEL site, (2) developing corresponding cumulative 30-day time series of precipitation and SWE for each site, and (3) evaluating the reliability of the time series as judged by consistency with neighboring SNOTEL sites and with the other precipitation data sets discussed in Subsection 2.6. The observed SNOTEL 24-hr precipitation value used for project analyses was the larger of the daily precipitation or SWE increment, since undercatchment of precipitation by the gage in strong winds and windblown loss of snow off the pillow sensor likely caused low biases in both data sets. The quality control showed that two of the 63 SNOTEL sites on Grid 3 had unreliable data over some or all of the 30 selected days, thus only 61 SNOTEL sites were utilized.

Appendix 5 consists of tables showing the Model simulated and SNOTEL observed daily precipitation at each of the 61 SNOTEL sites for each of the 30 selected days. In addition, Appendix 5 includes Model control simulated precipitation minus SNOTEL observed precipitation difference tables. The data are in two sets of tables, one for the 30 SNOTEL sites used in the MRBP statistical analysis (see Subsection 3.4), and another for the other 31 SNOTEL sites that were not used in the MRBP study. The appendix includes summary tables for both the 30 MRBP study days and the 31 non-MRBP study days, ranked by differences. There was very little difference in the findings for two data sets.

Table 3.1 summarizes the 30 selected cases in terms of the 61 SNOTEL site average model simulated and SNOTEL observed precipitation, the difference in average 24-hr precipitation (model – SNOTEL), and the ratio of average model to SNOTEL observed precipitation. The 30 cases are ranked in decreasing order of difference in average model and observed precipitation. The 61-site average 24-hr precipitation differences ranged from seven high-difference cases of over 10 mm, to seven low-difference cases with small negative values, i.e., where the average SNOTEL observed precipitation was slightly greater than the model simulated precipitation.

In general, the ranking by difference in average precipitation was matched by a decreasing ratio of average model to observed precipitation. Both the difference and ratio columns in Table 3.1 show a general strong bias in over-prediction of model simulated precipitation, with 23 of the 30 cases showing a positive model-observed difference and a ratio exceeding 1.0. The average model simulated precipitation over-prediction ratio for the 30 days was 1.88. The ten days with ratios of 2.0 or greater included all seven of the TROPA wind regime events. There were two cases with SSW wind regimes where the ratios exceeded 5.0. The model over-simulated precipitation in these and most of the other higher-ratio and higher-difference cases was likely due to over-simulated convection, when little or only relatively shallow convection actually occurred. This was likely related to the high temperature bias discussed in Subsection 3.6.

Table 3.1. 61-site/30-day Model and SNOTEL precipitation comparison
(1 mm = 0.03937 in.)

Summary of Model Control Run Precipitation Simulations vs Snotel Observations at 61 Snotel Sites for 30 Selected Operational Cloud Seeding Days						
Rank by Difference		**61-site average 24-hr precip. (mm)**			**M/S Ratio**	**Wind Regime**
	Date	**Model**	**Snotel**	**Difference**		
1	40222	17.95	2.12	15.83	8.47	SSW
2	31208	23.99	11.62	12.37	2.06	TROPA
3	40102	27.08	14.82	12.26	1.83	WSW
4	31221	15.30	4.08	11.22	3.75	TROPA
5	31110	20.97	10.62	10.35	1.97	WSW
6	40131	16.15	5.95	10.20	2.71	TROPA
7	40224	12.43	2.33	10.10	5.33	SSW
8	31226	13.48	5.08	8.40	2.65	TROPA
9	31215	14.77	6.54	8.23	2.26	NNW
10	31122	13.43	5.29	8.14	2.54	TROPA
11	31117	18.98	12.12	6.86	1.57	WNW
12	40103	16.16	9.83	6.33	1.64	WSW
13	40229	13.81	7.74	6.07	1.78	NNW
14	40204	12.36	6.50	5.86	1.90	NNW
15	40208	8.48	2.71	5.77	3.13	TROPA
16	31126	10.31	5.16	5.15	2.00	WNW
17	31103	14.95	10.04	4.91	1.49	SSW
18	31114	9.22	5.16	4.06	1.79	WSW
19	31227	7.05	3.21	3.84	2.20	TROPA
20	40205	5.06	2.83	2.23	1.79	NNW
21	40129	4.52	2.83	1.69	1.60	WNW
22	31213	7.62	6.08	1.54	1.25	WNW
23	31111	5.27	4.75	0.52	1.11	WNW
24	40128	2.91	3.04	-0.13	0.96	W
25	31127	1.71	2.00	-0.29	0.86	NNW
26	31118	1.70	2.29	-0.59	0.74	NW
27	31230	6.23	6.83	-0.60	0.91	WSW
28	31125	2.87	4.79	-1.92	0.60	W
29	31105	3.36	5.41	-2.05	0.62	SW
30	31107	0.09	2.66	-2.57	0.03	SW
	Total	328.23	174.43	153.80	**1.88**	
	Average	10.94	5.81	5.13	**1.88**	

The model's simulated precipitation over-prediction bias is domain-wide, as seen in a plot of 30-day total control run vs. observed precipitation for each of the 61 SNOTEL sites (Figure 3.2). Only one site shows a 1:1 ratio in 30-day model to observed precipitation, with all others showing a positive bias.

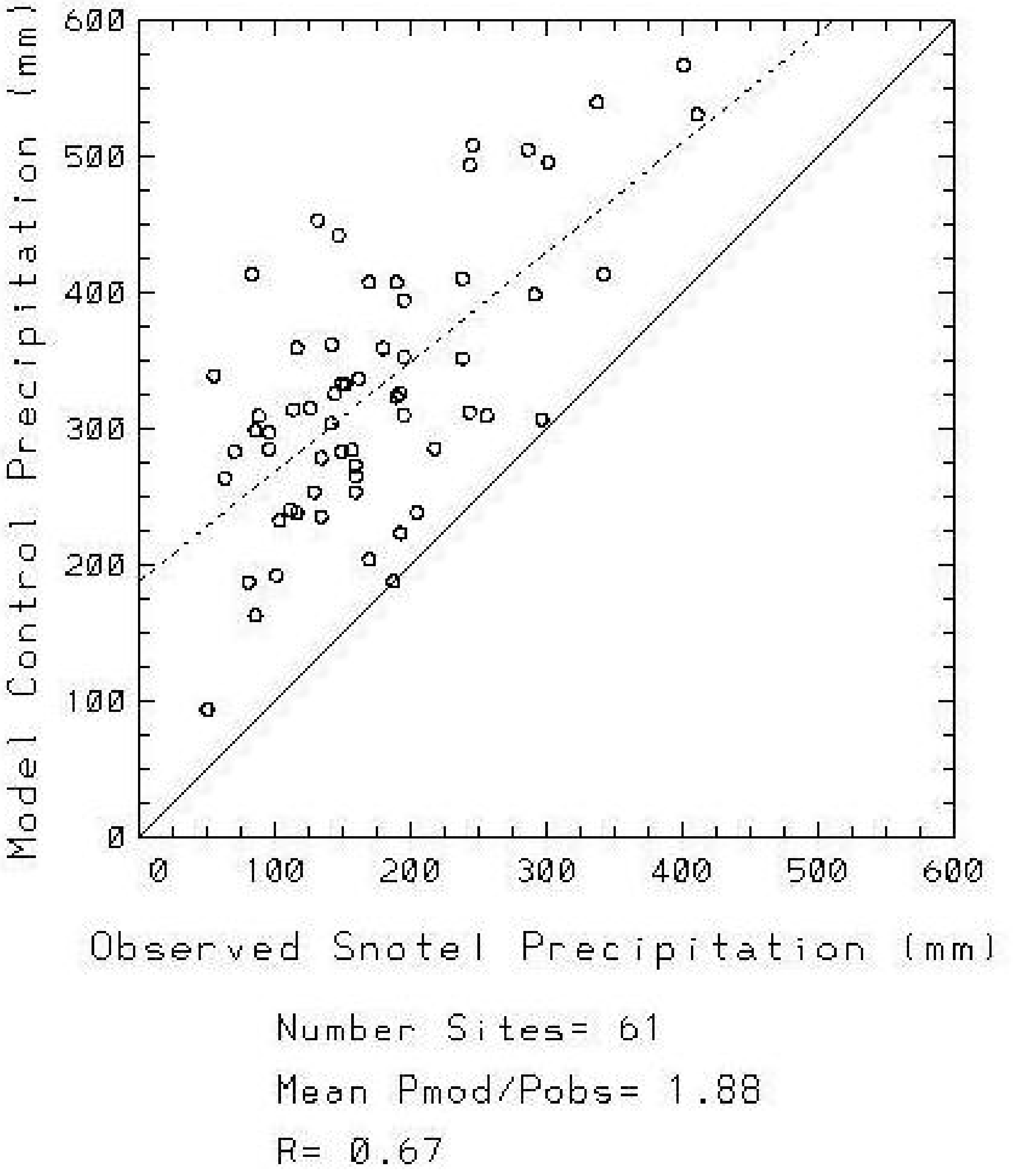


Figure 3.2. Plot of 30-day total model control vs. observed precipitation at 61 SNOTEL sites. (The dashed line is the line of best fit.)

There appears to be a geographical dependence on the model simulated precipitation over-prediction bias. This was determined by analyzing the model simulated vs. observed SNOTEL precipitation data by geographic area. The data were grouped into nine geographical areas as shown in Figure 3.3 and listed Table 3.2. The 30 SNOTEL sites in Figure 3.3 with red numbers were used in the MRBP study. Areas 1 and 2 include SNOTEL sites in or very near the western and eastern seeding Target Area, respectively, and Areas 3-9 extend from there in a generally counter-clockwise direction.

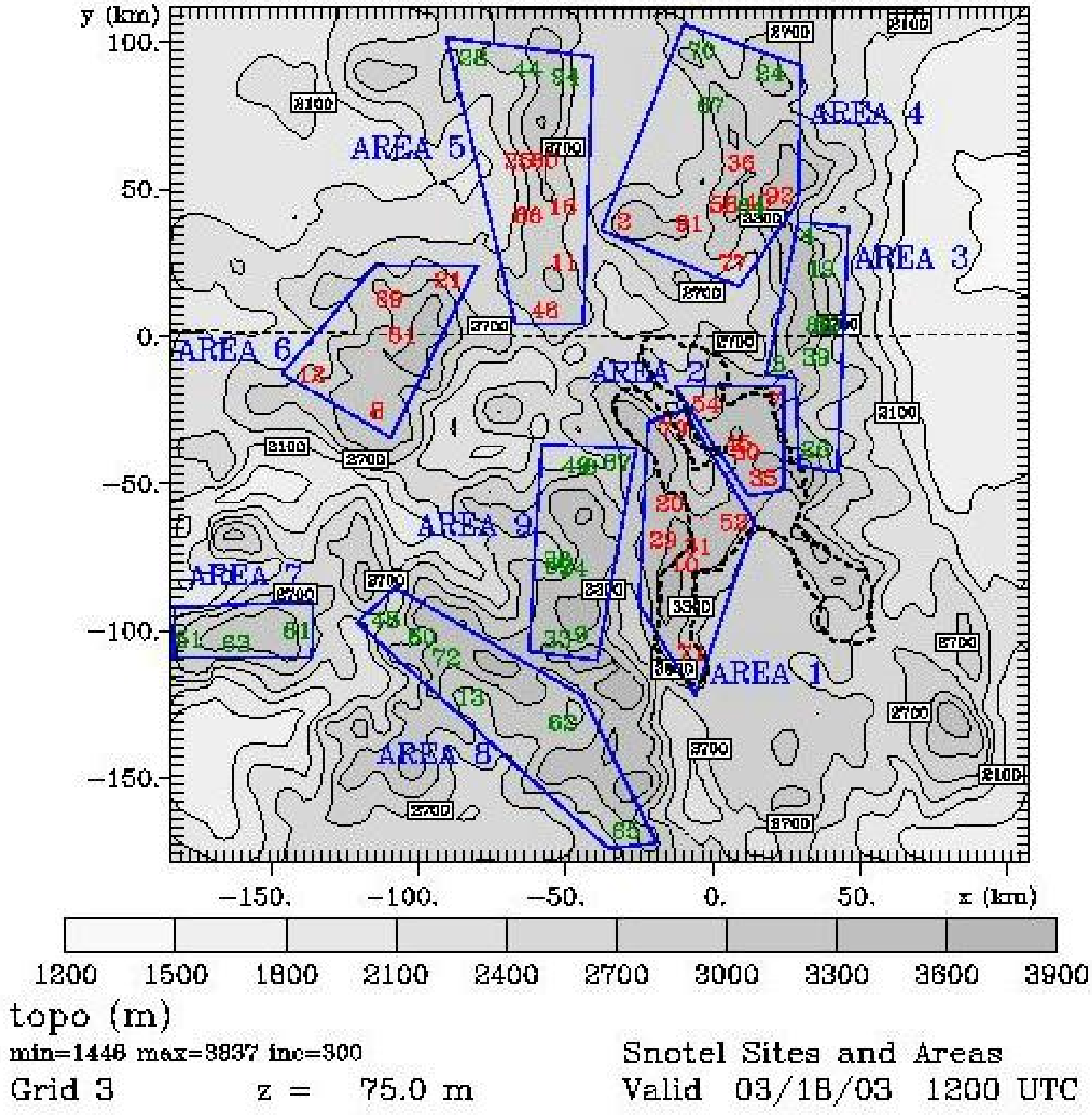


Figure 3.3. The 61 SNOTEL sites used in project evaluations on RAMS Grid 3, grouped into Areas 1-9, with shaded topography and Target Area boundary.

Table 3.2. SNOTEL site IDs used in 30-day analysis, grouped by area

SNOTEL Area	Geographic Description	# SNOTEL Stations	SNOTEL IDs
			30 MRBP sites 31 other sites
Area 1	Western Target Area	7	79 20 52 29 31 10 71
Area 2	Eastern Target Area	5	54 7 45 30 35
Area 3	Eastern Front Range	7	4 19 59 83 39 3 26
Area 4	Northern Front Range	11	70 24 67 36 92 40 64 58 91 2 77
Area 5	Park Range	9	28 44 94 80 25 16 66 11 46
Area 6	Flattops	5	21 69 81 12 8
Area 7	Grand Mesa	3	61 63 51
Area 8	Western Central Rockies	6	48 60 72 13 62 65
Area 9	Northern Central Rockies	8	87 49 6 38 57 34 9 33

Table 3.3 gives the area-averaged 30-day model and observed precipitation, and their difference and ratio, for each of the areas. Areas 1-4 and Area 9 all have mean high-bias ratios exceeding the 61-site average bias of 1.88, while Areas 5-8 all have mean biases less than the average of 1.88. The higher-bias areas include the Target Area, Area 9 just to the west, and the eastern and northern Front Range areas. The lower-bias areas are the more upwind areas in northwesterly to southwesterly events. This suggests that mountain precipitation is less over-predicted in relatively upwind, unobstructed portions of Grid 3 than in the more downstream mountain ranges that are blocked by features upstream. The physical mechanism(s) causing this relatively slight geographic bias in the model's over-prediction of precipitation is not clear.

Table 3.3. Average 30-day precipitation (mm) by SNOTEL areas
(model control run vs. SNOTEL observations)

	Average 30-day Precip (mm)			
SNOTEL Area	Model	SNOTEL	Difference	M/S Ratio
Area 1	248.31	117.20	131.11	2.12
Area 2	326.48	167.13	159.35	1.95
Area 3	316.67	136.43	180.24	2.32
Area 4	312.85	142.01	170.84	2.20
Area 5	381.16	245.53	135.63	1.55
Area 6	375.63	224.03	151.60	1.68
Area 7	365.93	247.23	118.70	1.48
Area 8	343.35	218.44	124.91	1.57
Area 9	315.83	135.57	180.26	2.33

The control simulations produced a reasonably accurate pattern of total precipitation and its topographic dependence for the 30 selected days. However, a strong model simulated precipitation over-prediction bias is evident over the entire Grid 3. This was most evident in TROPA wind regime cases and when convection was over-predicted by the model. The model over-prediction bias is slightly less severe in mountain locations located in the more upstream, unobstructed portions of Grid 3.

The CSU research team selected six of the 30 days for Lagrangian model simulation transport and dispersion case studies (Subsection 3.8). These six days selected are highlighted in yellow in Table 3.1. Additional maps of key parameters were made for these six days to assist in the interpretation and understanding of the case studies.

Figures 3.4 through 3.9 show 24-hr simulated no-seed (control) precipitation on RAMS 3-km grid for the six Lagrangian case study days. Although the model was initialized with 0000 UTC (Z) data, the 24-hr period for the precipitation is from 0800 UTC (0100 MST) of the date noted to 0800 UTC the following day.

Figure 3.4 shows 24-hr model simulated precipitation for a SSW wind flow regime. Table 3.1 shows that three of the 30 selected days were classified as having a SSW wind regime. The M/S ratio for this day was 1.49; however, the M/S ratios for the other two SSW wind regime days exceeded 5.0 (significant precipitation overprediction over RAMS grid 3). These ratios were computed using the 61 SNOTEL sites shown in Figure 3.3. This figure also shows that there were no SNOTEL sites located in the SE leg of the target area that could be used in computing the M/S ratios. Table 3.1 indicated a moderate precipitation event; the 61 SNOTEL sites averaged10.04 mm (0.40 in). Figure 3.4 shows that the model simulated precipitation within the target area south of the Continental Divide was light in comparison to the mountains to the SW of the target area.

Figure 3.5 shows 24-hr model simulated precipitation for a WSW wind flow regime. This was the heaviest precipitation event for the 30 selected days. Table 3.1 shows that the 61-SNOTEL-site average was 14.82 mm (0.58 in) with an M/S ratio of 1.83. If the SE leg of the target area is to get significant precipitation, it should be with SSW, SW, and WSW wind flow regimes. However, the model-simulated precipitation over the SE leg of the target area was generally always light, suggesting a possible shielding of this area by higher mountains located upwind SW-NW.

Figure 3.6 shows a second WSW wind flow regime day, but which only had about one-third the observed precipitation as in Figure 3.5. Table 3.1 shows that the 61-SNOTEL-site average was 5.16 mm (0.20 in) and the M/S ratio was 1.79. There was no model-simulated precipitation over the entire SE leg of the target area.

Figure 3.7 shows 24-hr model simulated precipitation for a WNW wind flow regime. Table 3.1 shows that the 61-SNOTEL-site average was 5.16 mm (same as for Figure 3.6) with an M/S ratio of 2.00. There was significant precipitation within both northern arms of the target area, but only light precipitation south of the Continental Divide. This precipitation pattern is what would be expected with WNW wind flow.

Figure 3.8 shows 24-hr model simulated precipitation for a NNW wind flow regime. Table 3.1 shows that the 61-SNOTEL-site average was 6.54 mm (0.26 in) with an M/S ratio of 2.26. There was significant precipitation over the NE arm of the target area, which is consistent with a NNW wind flow regime.

Figure 3.9 shows a second NNW wind flow regime day, with light precipitation over the entire RAMS Grid 3. However, the precipitation pattern was similar to Figure 3.8. Table 3.1 shows that the 61-SNOTEL-site average was 2.83 mm and the M/S ratio was 1.79.

Recall that Figure 3.1 showed the 30-day total control run simulated precipitation field. The 30-day total shows only light precipitation over the entire SE leg and south half of the SW leg of the target area. This total precipitation pattern is consistent with the 24-hr patterns in Figures 3.4–3.9. Thus the model indicates little orographic precipitation potential and perhaps little cloud seeding potential over the two south legs of the target area.

Possible causes of overprediction bias are:

- Resolution too coarse to represent entrainment in embedded cumuli?
- Precipitation efficiencies too high due to inadequate specification of background IFN and CCN.
- Moisture is not conserved in model due to RAMS computation algorithms.
- Vapor deposition growth is over-predicted by the model physics.

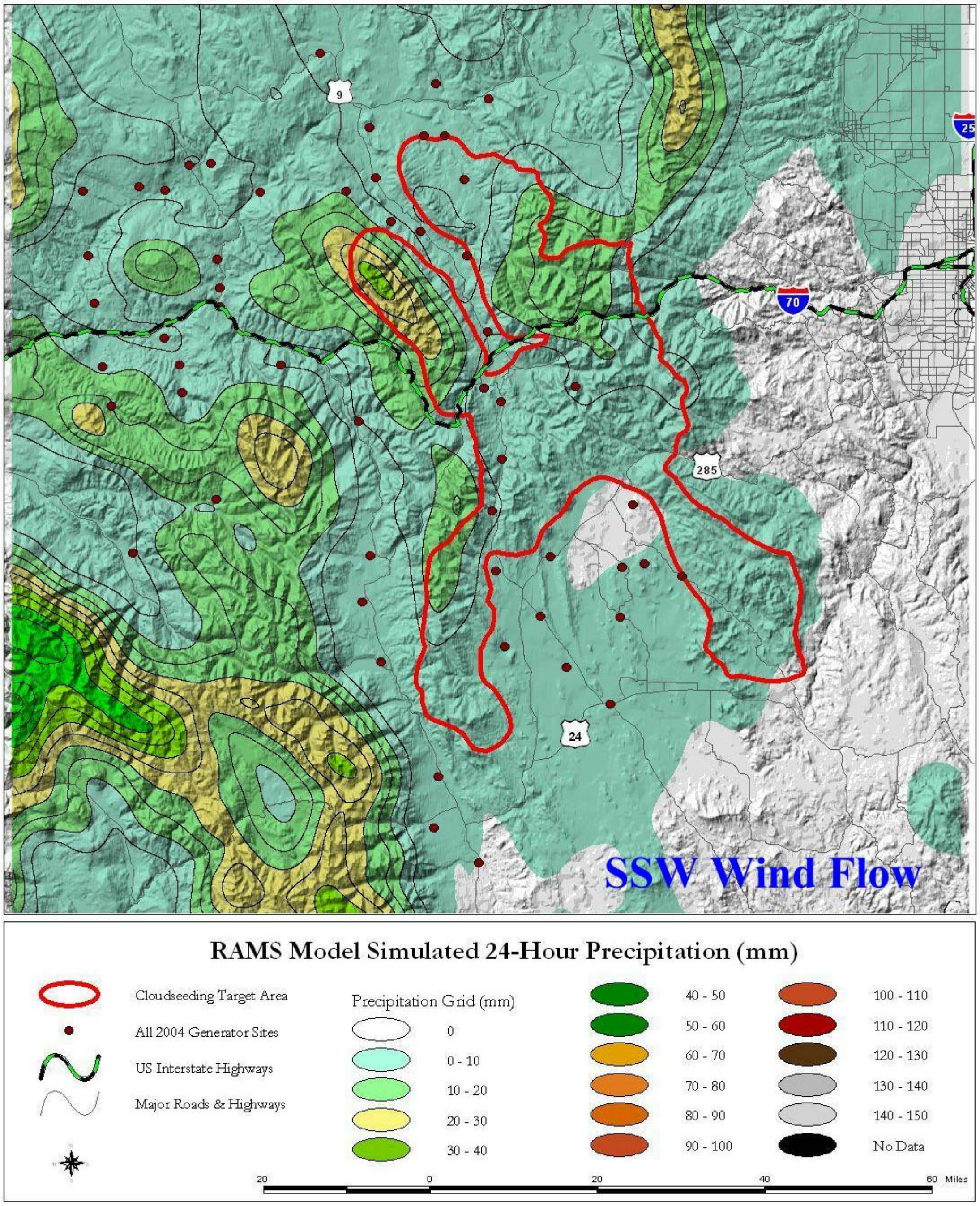


Figure 3.4. SSW Wind Flow Regime – Model Simulated 24-hr Precipitation for 0100 MST on November 3, to 0100 MST on November 4, 2003

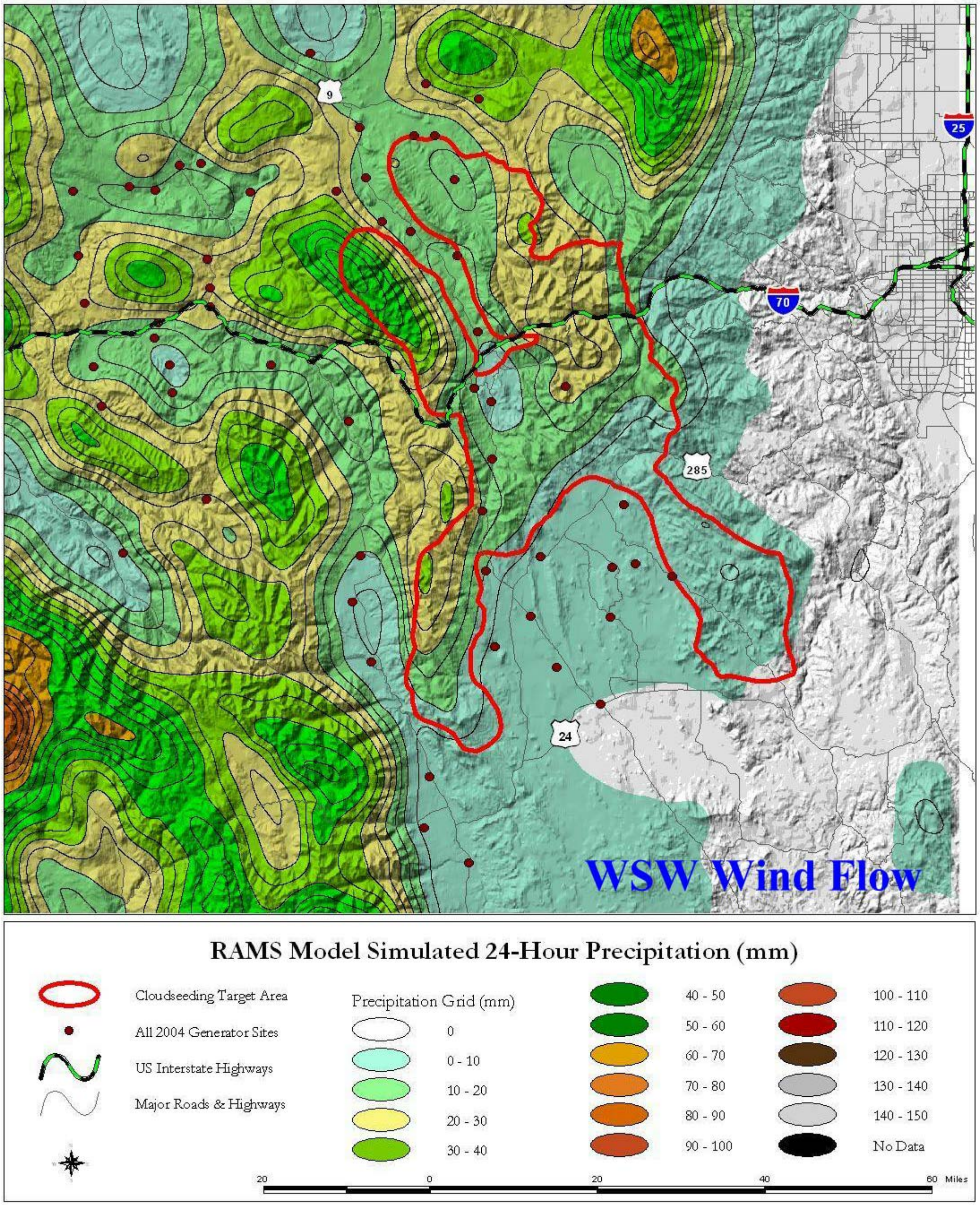


Figure 3.5. WSW Wind Flow Regime – Model Simulated 24-hr Precipitation for 0100 MST on January 2, to 0100 MST on January 3, 2004

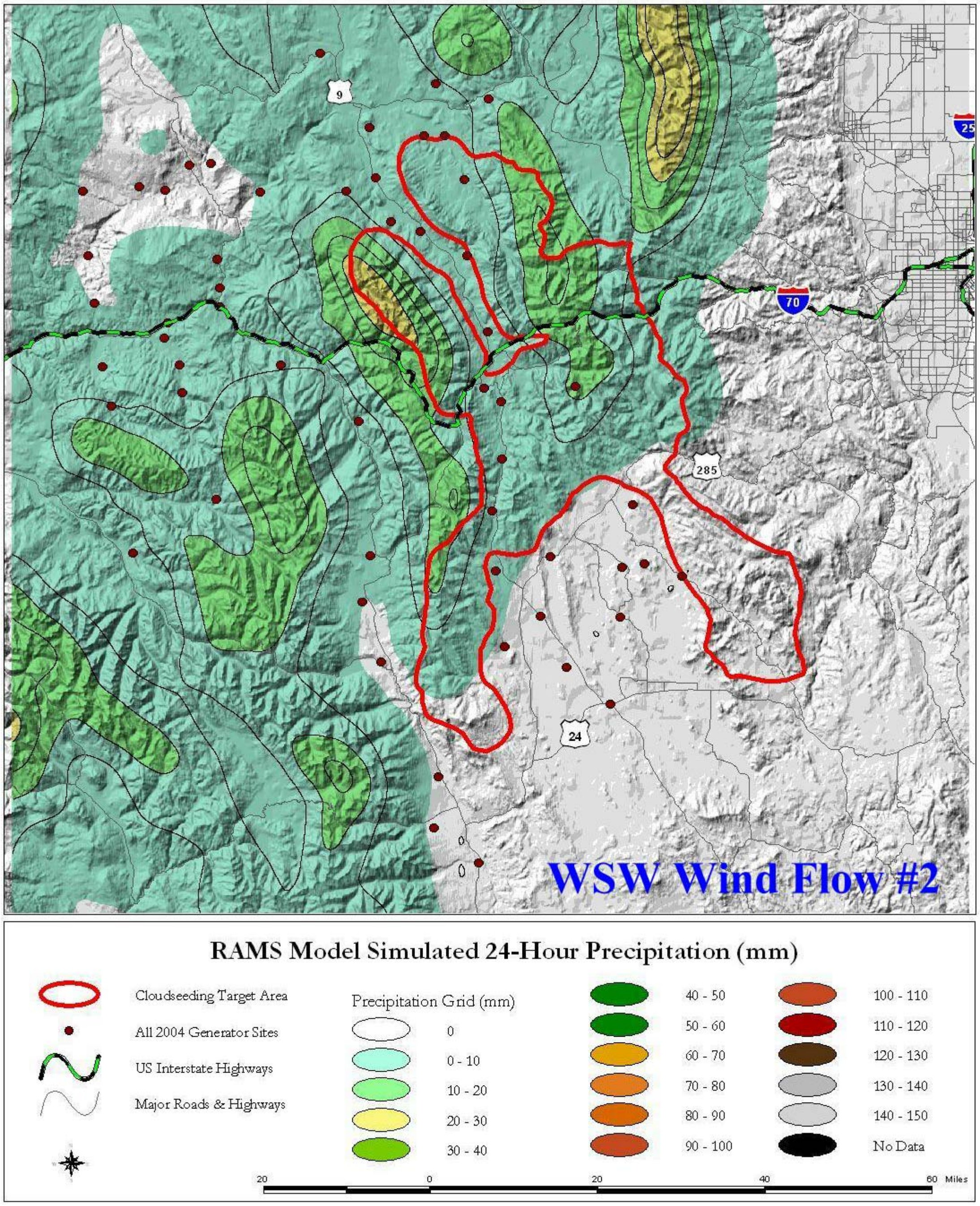


Figure 3.6. WSW Wind Flow Regime #2 – Model Simulated 24-hr Precipitation for 0100 MST on November 14, to 0100 MST on November 15, 2003

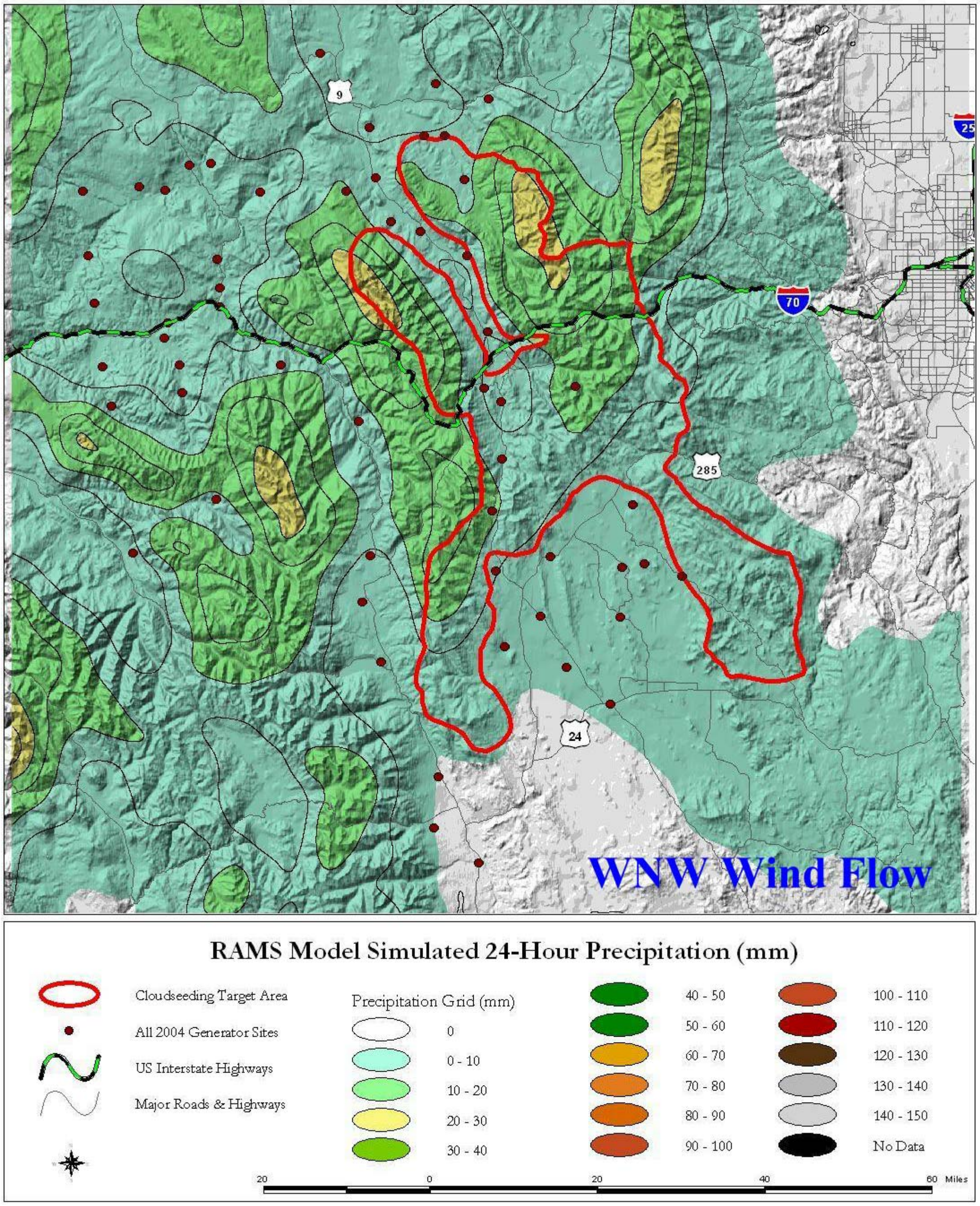


Figure 3.7. WNW Wind Flow Regime – Model Simulated 24-hr Precipitation for 0100 MST on November 26, to 0100 MST on November 27, 2003

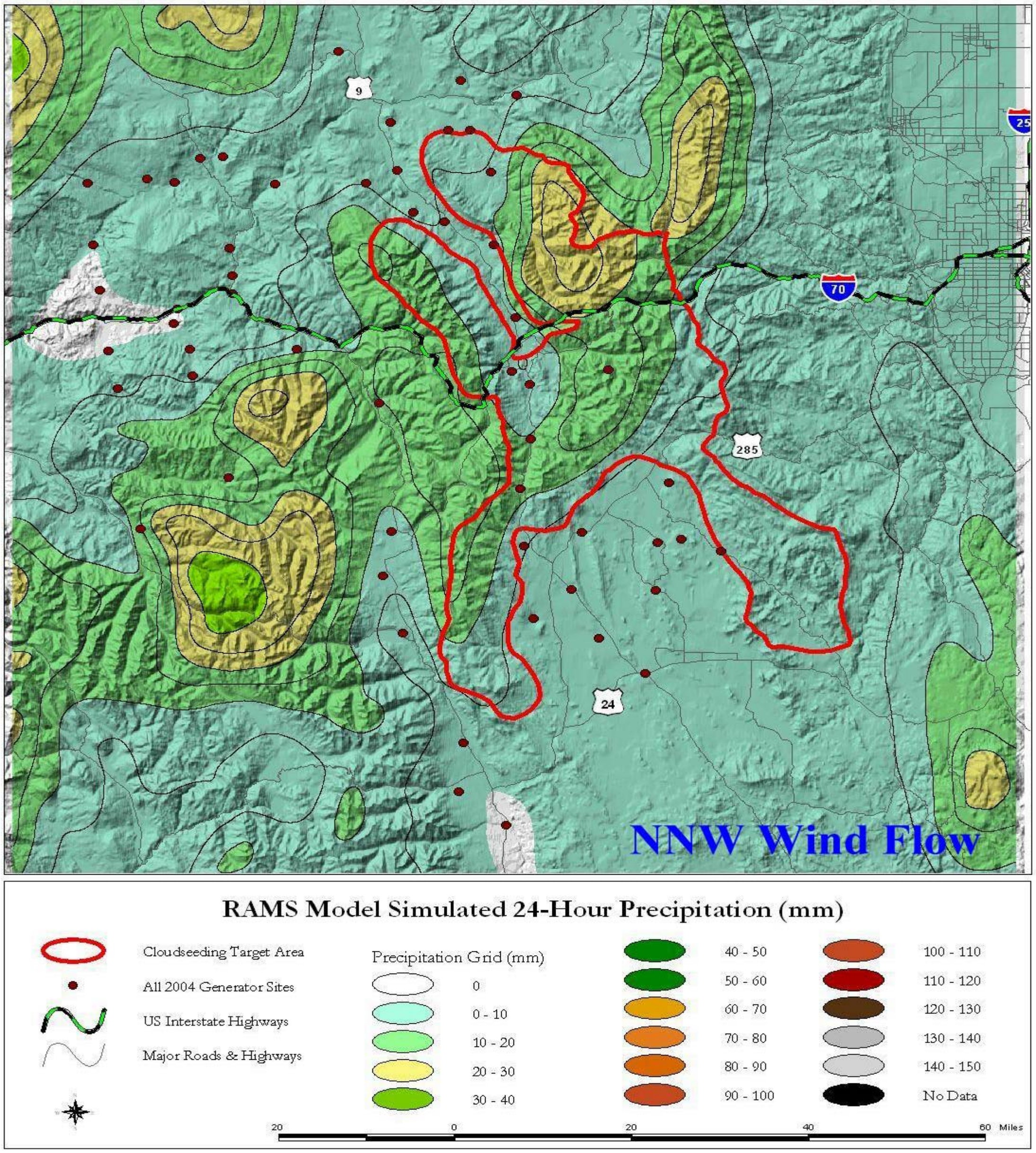


Figure 3.8. NNW Wind Flow Regime – Model Simulated 24-hr Precipitation for 0100 MST on December 15, to 0100 MST on December 16, 2003

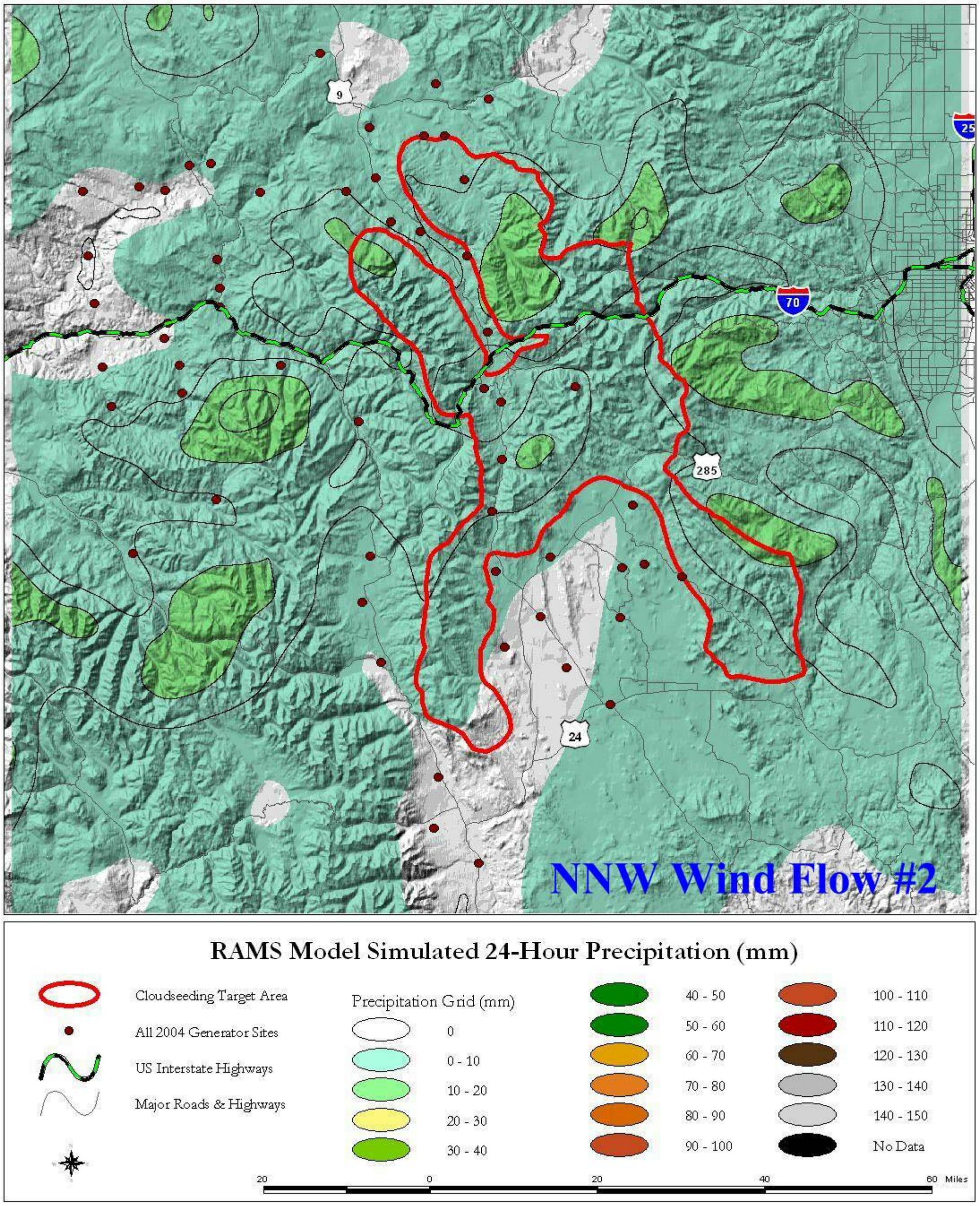


Figure 3.9. NNW Wind Flow Regime #2 – Model Simulated 24-hr Precipitation for 0100 MST on February 5, to 0100 MST on February 6, 2004

3.3 Comparison of Model Control and Seed Simulated Precipitation

The initial model sensitivity tests of control no-seed and seed simulated precipitation found that there were only small differences in the 24-hr simulated precipitation fields (see Subsection 2.8). After the final model production runs had been completed in September 2004, a Seed minus Control difference analysis was preformed on two data sets. One analysis used an 86-day data set that included all days on which some cloud seeding effects were possible. This included 8-hr to 32-hr forecast periods where some of the precipitation could have been affected by seeding operations that ended prior to that period. Also included in this 86-day set were the reverse situation days when seeding began late in one 24-hr precipitation evaluation period but was primarily targeted for the next 24-hr period. The second analysis used the 30 cloud seeding days selected for project evaluations (listed in Table 2.2).

The bulk of the simulated precipitation was associated with the 30-day data set. While the 30 days were only about 35% of all 86 possible seeding days, Grid 3 average precipitation for the 30 days was 56.2% of the total 86-day Grid 3 average, and the target area average precipitation for the 30 days was about 61.4% of the total 86-day average. The findings from these data analyses are listed in Table 3.4. There was essentially no difference between the 30-day seed and control average totals, or between the 86-day seed and control average totals.

Table 3.4. Average multi-day simulated precipitation totals (mm)
(difference = seed minus control; % = 30-day/86-day)

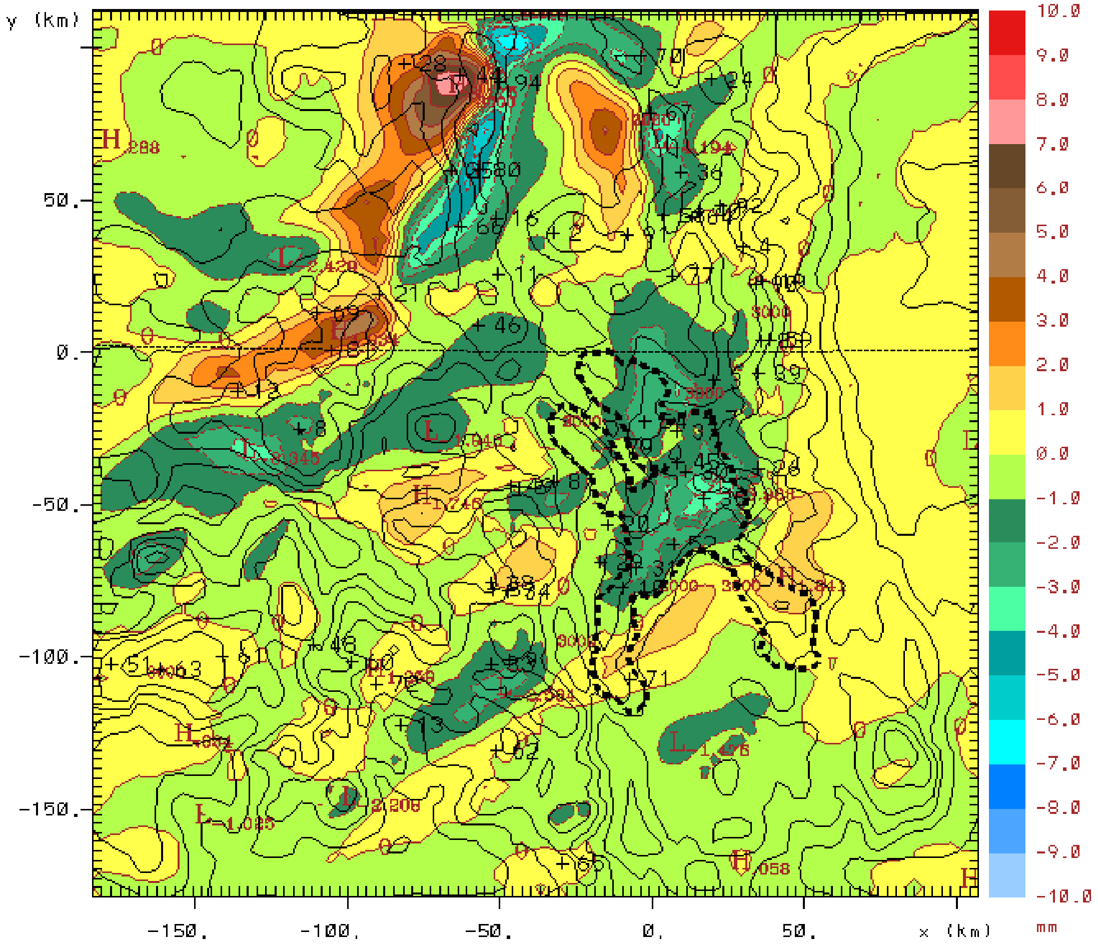
	Grid 3			**Target Area**		
Set	seed	control	difference	seed	control	difference
30 day	173.4	173.6	-0.2	232.2	233.3	-1.1
86 day	308.6	308.8	-0.2	379.0	380.0	-1.0
%	56.2	56.2		61.3	61.4	

There were three figures generated for each analysis:

- 30-day total Control run simulated precipitation
- 30-day total Seed run simulated precipitation
- 30-day total Seed – Control simulated precipitation
- 86-day total Control run simulated precipitation
- 86-day total Seed run simulated precipitation
- 86-day total Seed – Control simulated precipitation

Visually there was no difference between the 30-day Control and Seed run totals, and the 86-day Control and Seed totals. Likewise the Seed minus Control difference figures for the 30-day and 86-day analyses looked very similar. These visual conclusions were supported by the findings in Table 3.4.

Since the focus of the project's evaluations was on the selected 30-day set, just the figures for the 30-day total control run simulated precipitation field (Figure 3.1, Subsection 3.2) and 30-day total Seed-Control difference (Figure 3.10) were included in this report.



Select 30seed-day S-C Pcp		grid 3			
	2004-03-01-0800.00 UTC	min	max	inc	lab*
contours	season precip (mm)	-6.867	8.175	1.000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 3.10. 30-day total Seed-Control Grid 3 precipitation difference.

Visually the difference patterns in Figure 3.10 looks significant, but the difference scale along the right side of the figure provides for a maximum value of 10.0 mm (0.4 in); the maximum 24-hr difference indicated in the figure is nearly 10.0 mm (0.4 in) for 30 days. The larger positive difference values to the distant northwest of the target area are difficult to understand, especially with high mountainous terrain between the positive values and the target area. North of the Continental Divide within the target area where the heaviest precipitation was observed and simulated by the model, the difference values were slightly negative (about –2 mm).

Looking at the individual daily differences shows that the larger positive values to the northwest were mainly due to the differences on two days, viz. February 22, 2004 and December 26, 2003. Evaluation of the 24-hr simulated precipitation maps for control and seed runs (relative to the topography in the northern Park Range) for the February 22, 2004 case showed that the local precipitation max in that region (~30 mm) was a little further ENE in the control run. It was this spatial shift that resulted in the strong +/- couplet in precipitation difference. The 2-hr precipitation rate fields for this case (not shown) indicated that this local maximum was convective in nature and tied to the 24-hr precipitation pattern extending SSW to the Flattops. It was speculated by CSU project researchers that the slight spatial shift in that convective feature between control and seed runs was probably due to very weak gravity waves, or just small variations in convective initiation due to the very small dynamic response to the seeding.

Figures 3.11 through 3.16 show 24-hr model simulated seed minus no-seed (control) precipitation differences on RAMS 3-km grid for the six Lagrangian case study days. Although the model was initialized with 0000 UTC (Z) data, the 24-hr period for the precipitation is from 0800 UTC (0100 MST) of the date noted to 0800 UTC the following day.

Figure 3.11 shows the 24-hr model simulated seed minus no-seed precipitation difference for a SSW wind flow regime. Over the target area the differences range from about –0.25 mm (0.01 in) to +0.25 mm (0.01 in). This indicates that the model simulated precipitation seed and no-seed runs were essentially the same.

Figure 3.12 shows the 24-hr model simulated seed minus no-seed precipitation difference for a WSW wind flow regime. This figure shows slightly larger differences over the target area north of Interstate 70. The differences ranged from about –1.00 (0.04 in) to +0.05 (0.02 in). This 24-hr period had the largest differences for the six cases studied. Figure 3.13 shows a second WSW wind flow regime. The model simulated precipitation seed and no-seed runs were essentially the same, with maximum differences of about 0.25 mm (0.01 in).

Figure 3.14 shows the 24-hr model simulated seed minus no-seed precipitation difference for a WNW wind flow regime. This figure shows the differences aligned with the wind flow, as discussed in Subsection 2.8 and shown in Figure 2.15. The differences over the target area were about 0.25 mm.

Figures 3.15 and 3.16 show the 24-hr model simulated seed minus no-seed precipitation difference for two WNW wind flow regimes. Over the target area the differences range from about –0.25 mm (0.01 in) to +0.25 mm (0.01 in).

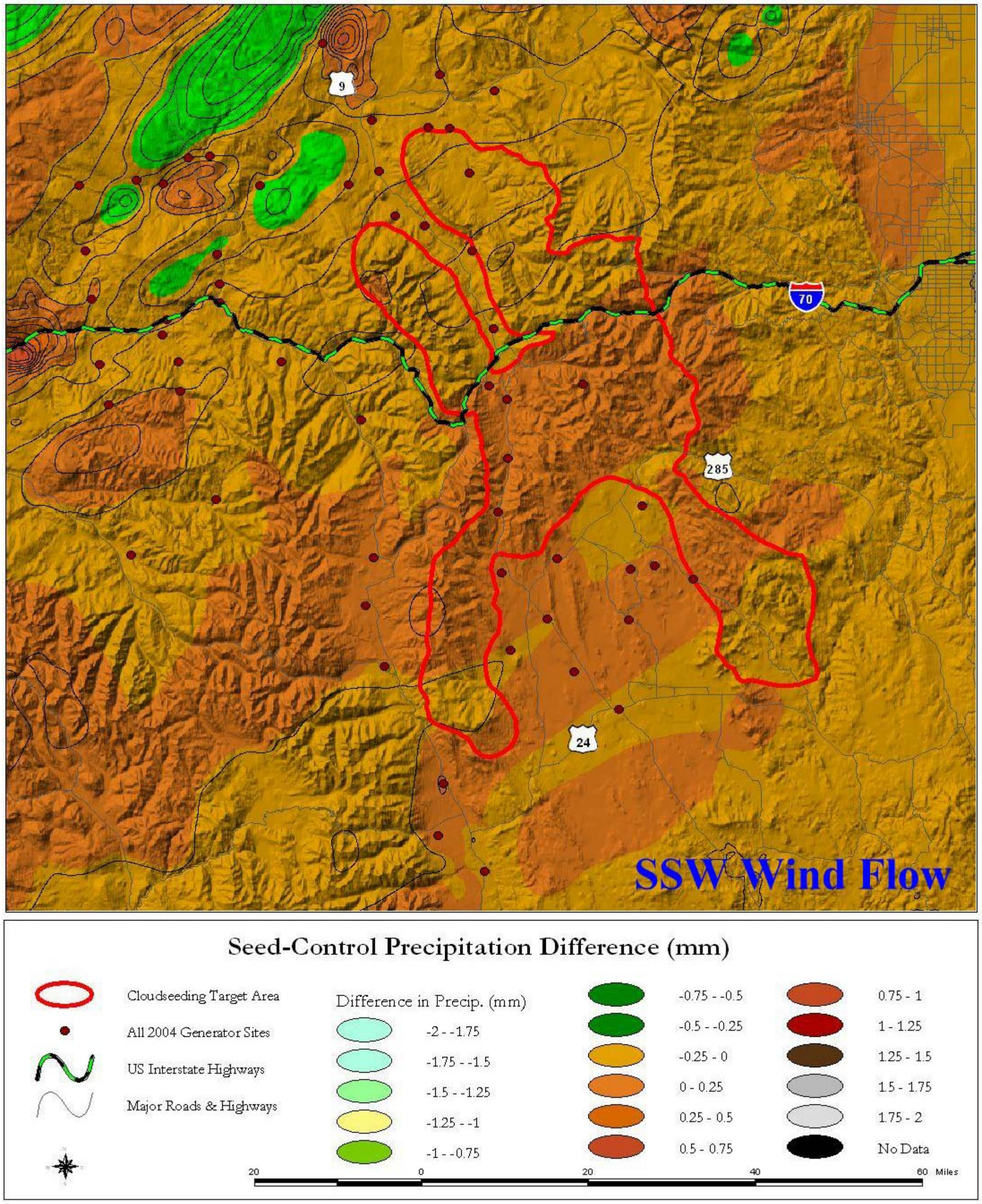


Figure 3.11. SSW Wind Flow Regime – Model Simulated
Seed minus Control 24-hr Precipitation Difference
for 0100 MST on November 3, to 0100 MST on November 4, 2003

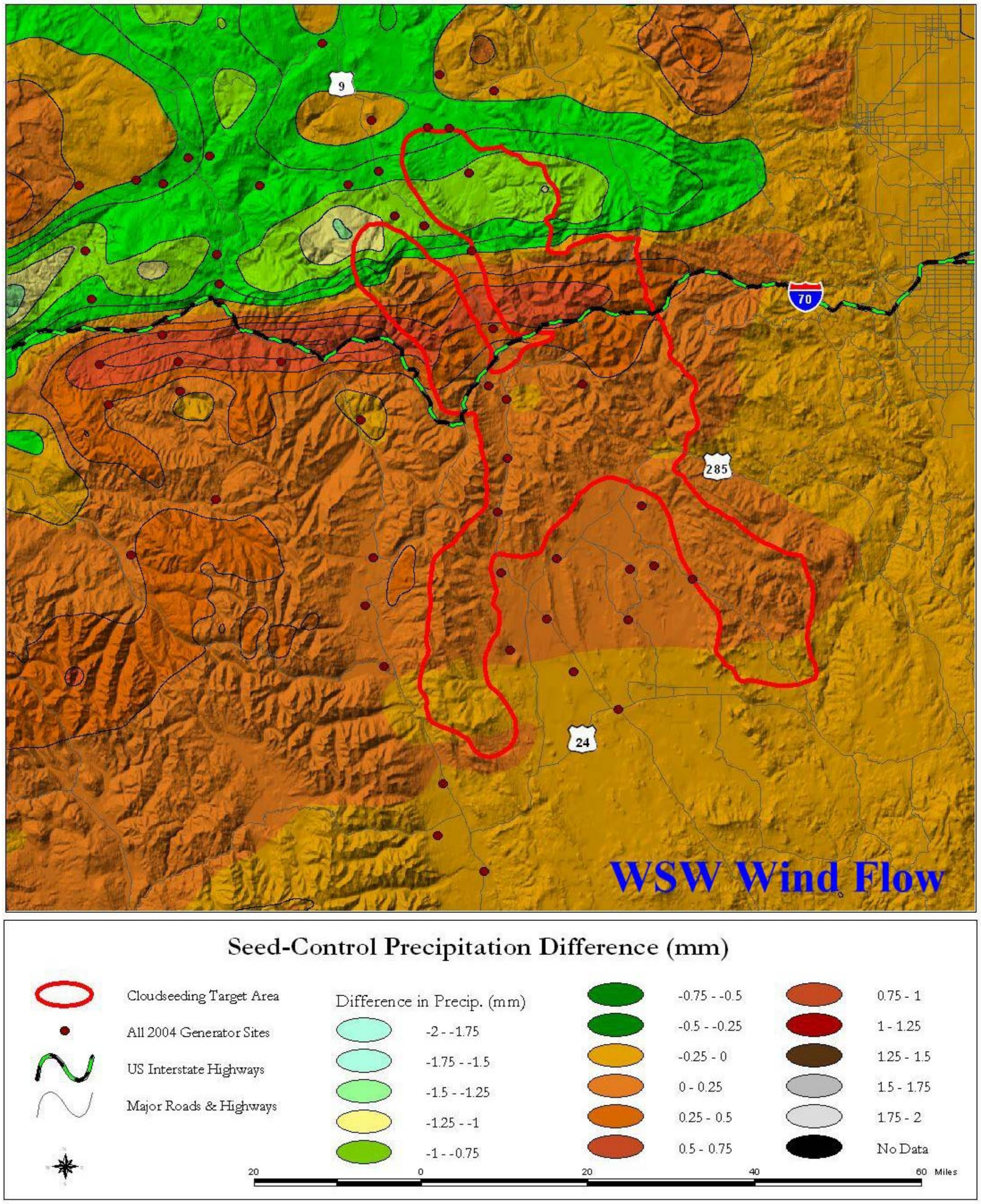


Figure 3.12. WSW Wind Flow Regime – Model Simulated
Seed minus Control 24-hr Precipitation Difference
for 0100 MST on January 2, to 0100 MST on January 3, 2004

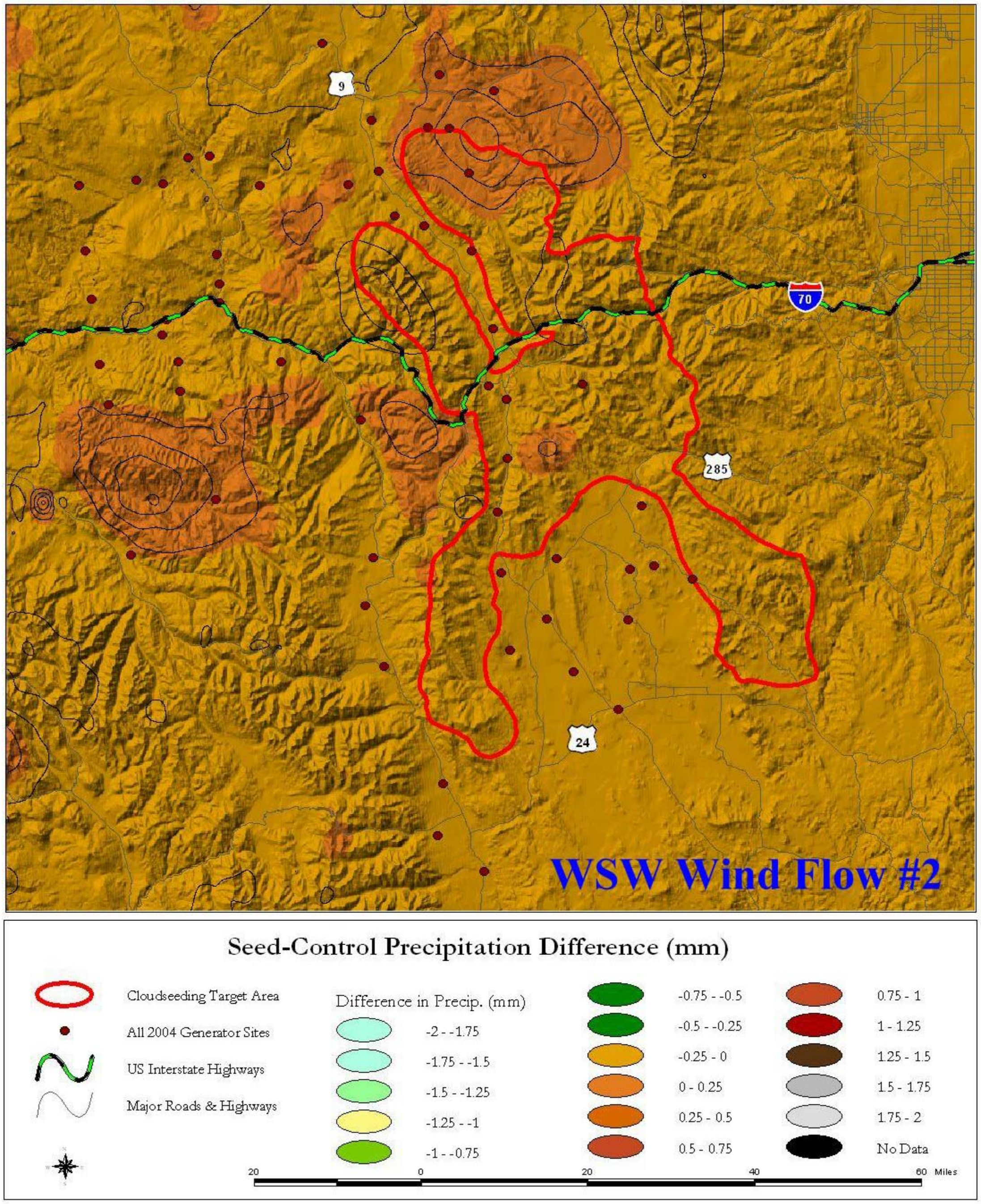


Figure 3.13. WSW Wind Flow Regime #2 – Model Simulated
Seed minus Control 24-hr Precipitation Difference
for 0100 MST on November 14, to 0100 MST on November 15, 2003

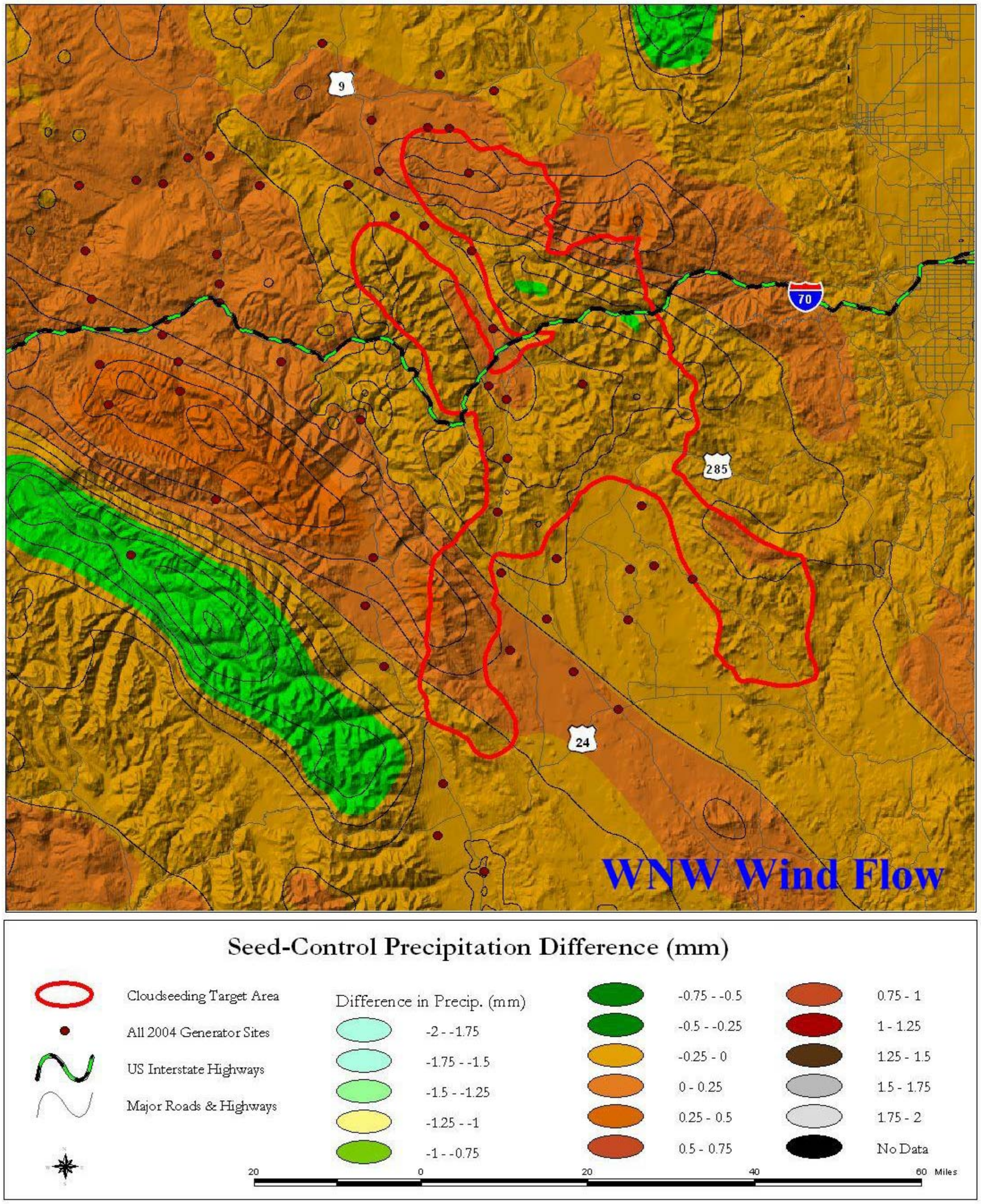


Figure 3.14. WNW Wind Flow Regime – Model Simulated
Seed minus Control 24-hr Precipitation Difference
for 0100 MST on November 26, to 0100 MST on November 27, 2003

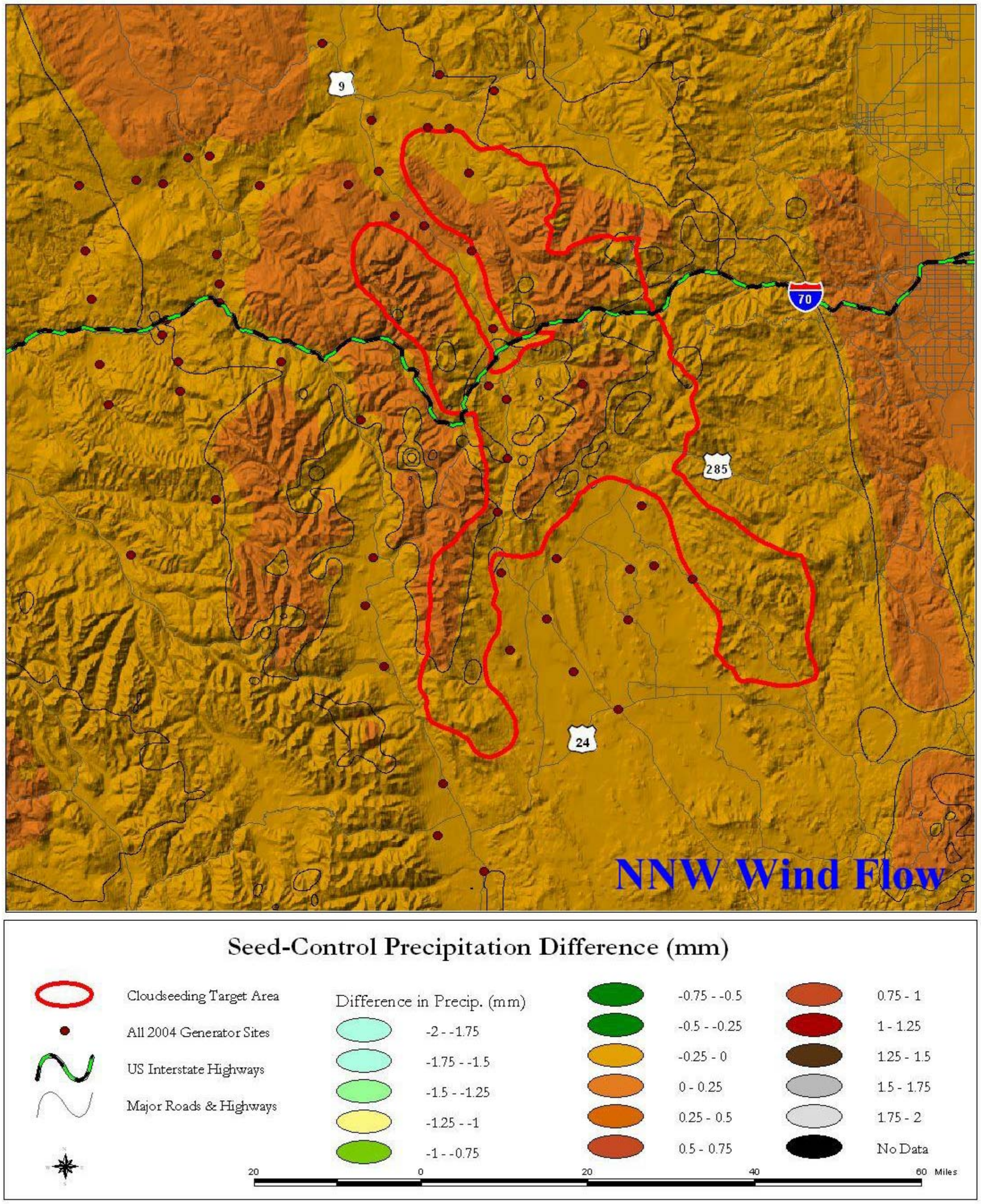


Figure 3.15. NNW Wind Flow Regime – Model Simulated
Seed minus Control 24-hr Precipitation Difference
for 0100 MST on December 15, to 0100 MST on December 16, 2003

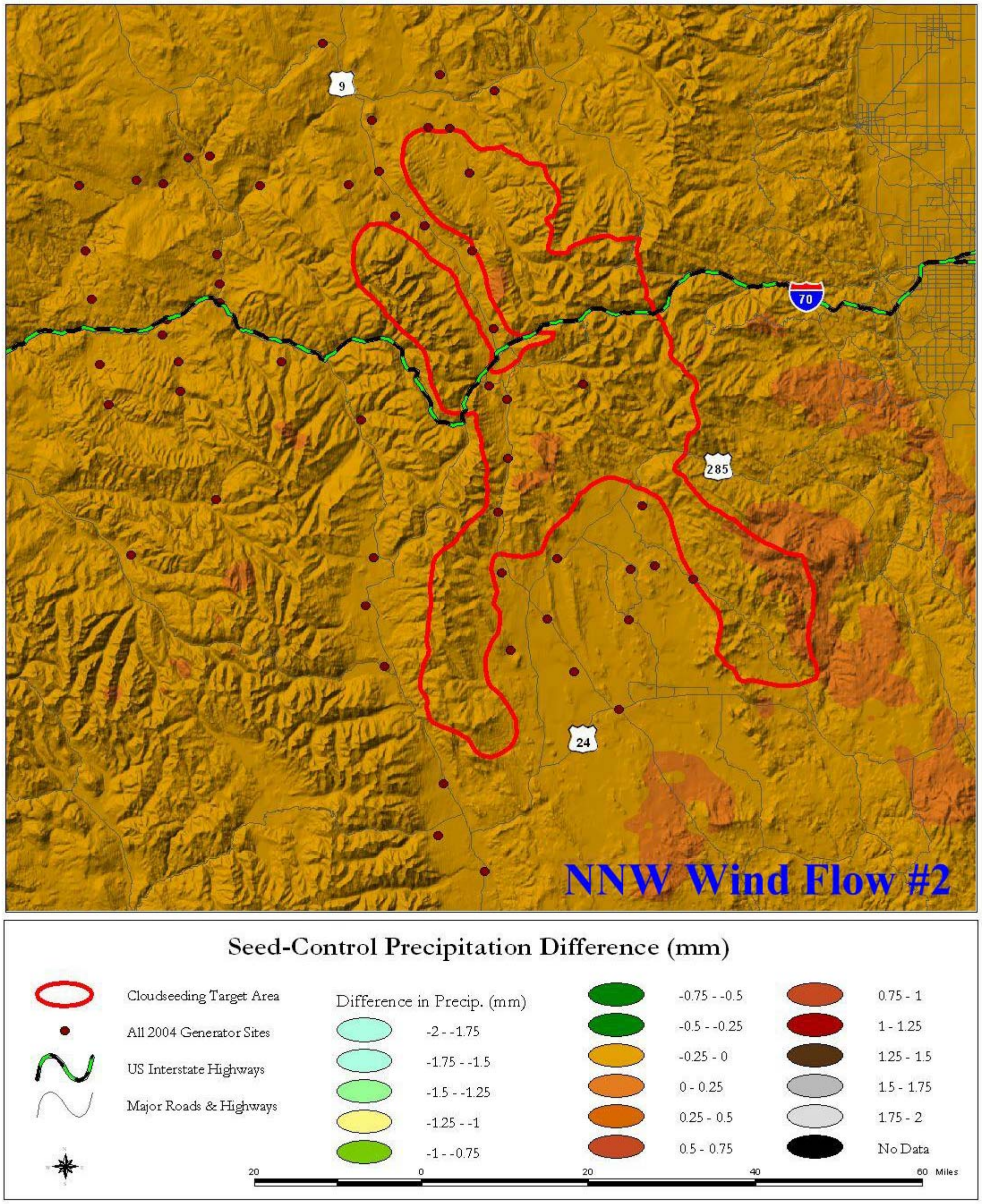


Figure 3.16. NNW Wind Flow Regime #2 – Model Simulated
Seed minus Control 24-hr Precipitation Difference
for 0100 MST on February 5, to 0100 MST on February 6, 2004

The primary finding from the RAMS model simulated precipitation seed vs. no-seed comparison is that the simulated seeding effects on microphysical processes and precipitation are rather limited. The very small differences between model seed and no-seed simulated 24-hr precipitation could be because:

- The background CCN and IFN concentrations are unknown; therefore, the results are at the mercy of specified background concentrations. If background IFN is too high, seedability would be reduced. If background CCN concentrations are too high, we expect seedability would be reduced as well.

- The model under-predicts supercooled liquid water (SLW) content in the lower portion of clouds over the target area, thereby reducing seedability. If this is the case this could be a result of to large background IFN concentrations.

- An unforeseen dynamic response that appears to result in large areas of slightly suppressed precipitation in the target area and small regions of slightly enhanced precipitation.

- A low-level warm temperature bias in the model results in delayed AgI nuclei activation, fewer activated nuclei, and less time for crystals to grow and snow to fall in the target area. The magnitude of the warm bias appears to be too small to have a major impact on seedability.

- The transport and diffusion of seeding material from the generator sites is getting into the clouds too far downwind of the generator sites.

3.4 Model Background and Seed Ice Forming Nuclei Concentrations

The version of the RAMS model used on the Colorado WDMP explicitly represented orographic clouds and precipitation processes in mixed-phase clouds. RAMS had been demonstrated to be a good model on other CSU research projects; however, this was the first time that any such model had been applied to a full winter season cloud seeding project. It is also the first time the model had been evaluated over the central Colorado Mountains on the western slope. As stated in Subsection 2.5, algorithms were added to the model simulating sources of IFN from cloud-seeding generators.

The finding that there was essentially no difference in model simulated precipitation between seed and no-seed runs was unexpected. Dr. William Cotton, PI for CSU research team, has stated that one thing we have learned from this research project is that measurements needed to support the modeling effort (like CCN and IN) have to be done before we can ever predict differences between seeded and non-seeded clouds.

The project didn't have measurements of background IFN, CCN, & GCCN concentrations, and the version of RAMS that was used did not have a sub-grid cumulus scheme. However, the model did include a scheme to permit daily varying concentrations in IFN as well as vertically-varying IFN concentrations. Sensitivity studies were performed that included varying the background IFN concentration or using constant background IFN concentration fields vs. initial concentrations that could evolve through advection and diffusion. These experiments all produced similar results regarding the small sensitivity to seeding on precipitation amounts and the large-area manifestation of these slight differences.

The sensitivity tests showed that the model control 24-hr simulated precipitation amounts and patterns did not change significantly between the various background IFN experiments (on the order of a few percent at most). It is suspected that this lack of sensitivity is due to an abundance of background IFN regardless of how CSU researchers varied it. Although rather insignificant, these differences between different control sensitivity runs were still greater than the control vs. seed differences of any pair of control vs. seed sensitivity runs. In any such pair of control vs. seed runs in which, background IFN were altered identically for both, and they varied only due to the absence (presence) of seeded AgI in the control (seed) run, the differences were generally much less than 1% and are organized into the grid-wide banded patterns, i.e., the same "similar results" that were seen in the final set of control vs. seed runs. It would be desirable to run more sensitivity tests to study this problem, but lack of funding prevented this during the project.

There is not only the uncertainty of natural background concentrations, but also of model seeded AgI IN concentrations. The following Figures 3.17 – 3.22

show vertically integrated AgI concentrations on the RAMS Grid 3 for the six days selected for the Lagrangian case studies. The times of the maps were the times of maximum amount of vertically-integrated AgI as seen in the daily time series (available on the CSU Web site for this research project). The hours given in the labels for the maps (e.g. 10-Hour) are the number of hours from the time and date of model initialization.

The highest concentrations of vertically integrated AgI in the six figures were associated with ground-based AgI generator sites. However, there were significant concentrations of AgI cloud seeding material over portions of the target area. In all six figures, the northwest arm and southwest leg of the target area show the lowest concentrations of vertically integrated AgI. The reason for the lack of significant model simulated AgI concentrations in these portions of the target area is not understood and needs further study.

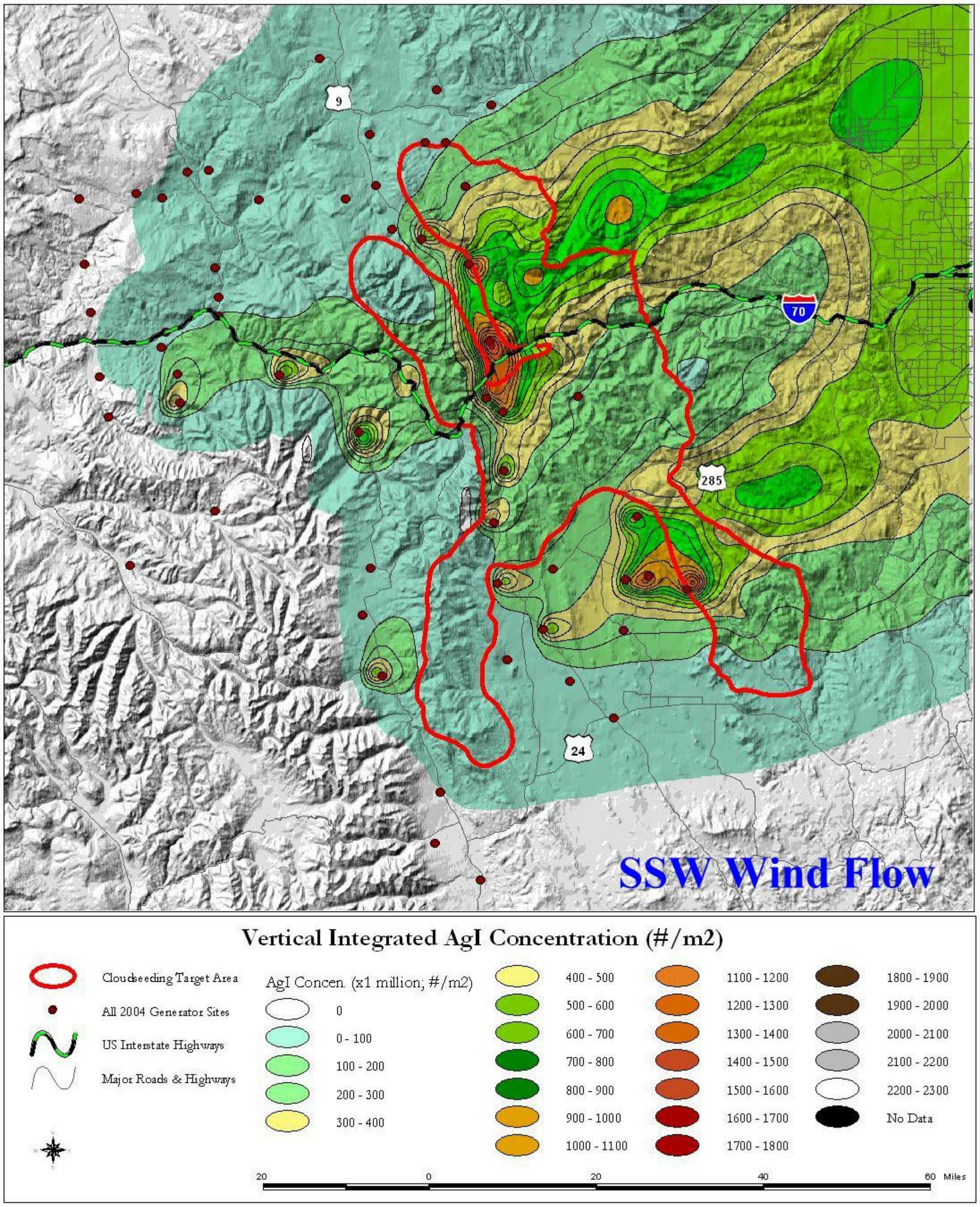


Figure 3.17. SSW Wind Flow Regime – Model Simulated
24-hr Vertical Integrated AgI Concentration
For 1700 MST on November 3, 2003

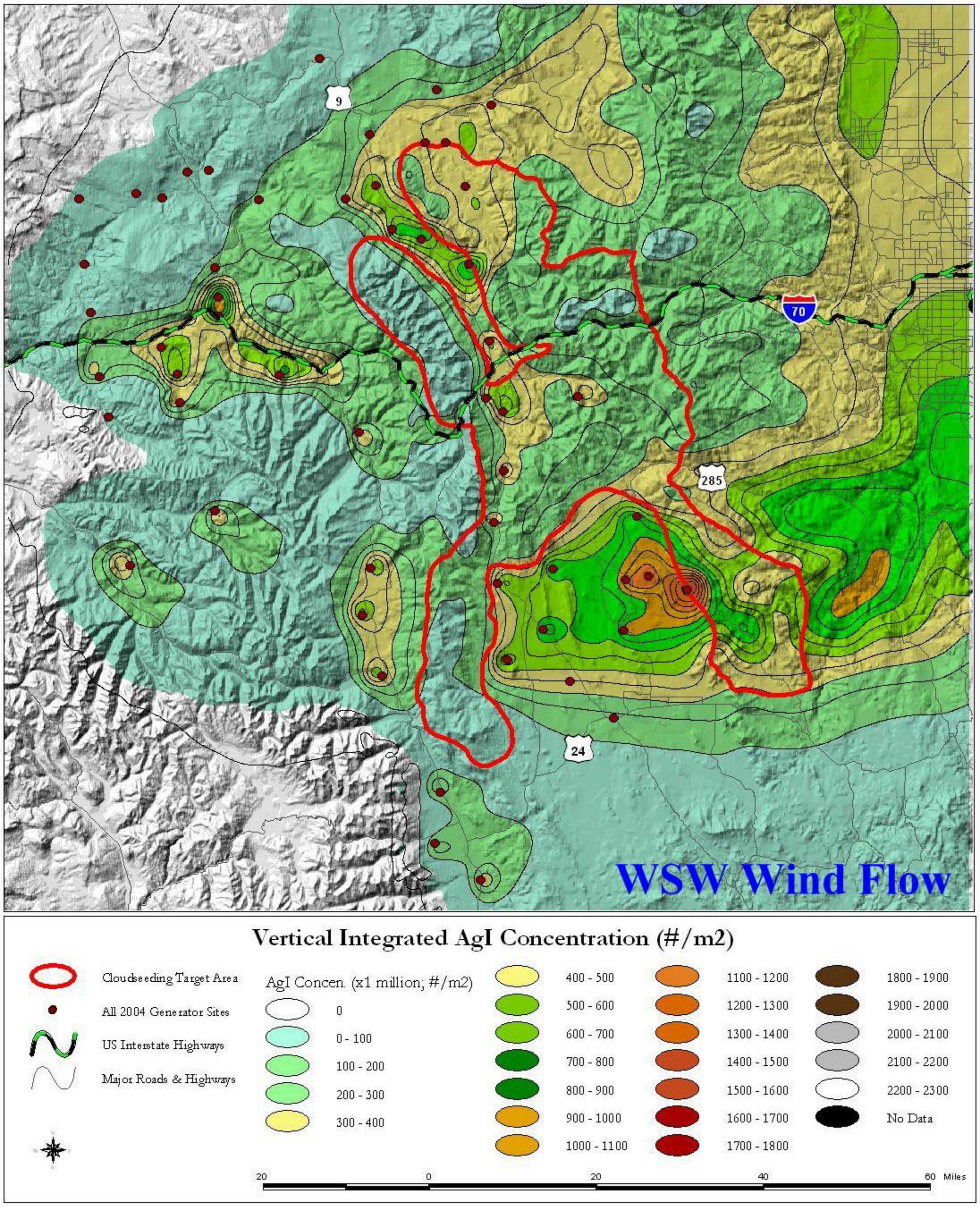


Figure 3.18. WSW Wind Flow Regime – Model Simulated
32-hr Vertical Integrated AgI Concentration
for 0100 MST on January 3, 2004

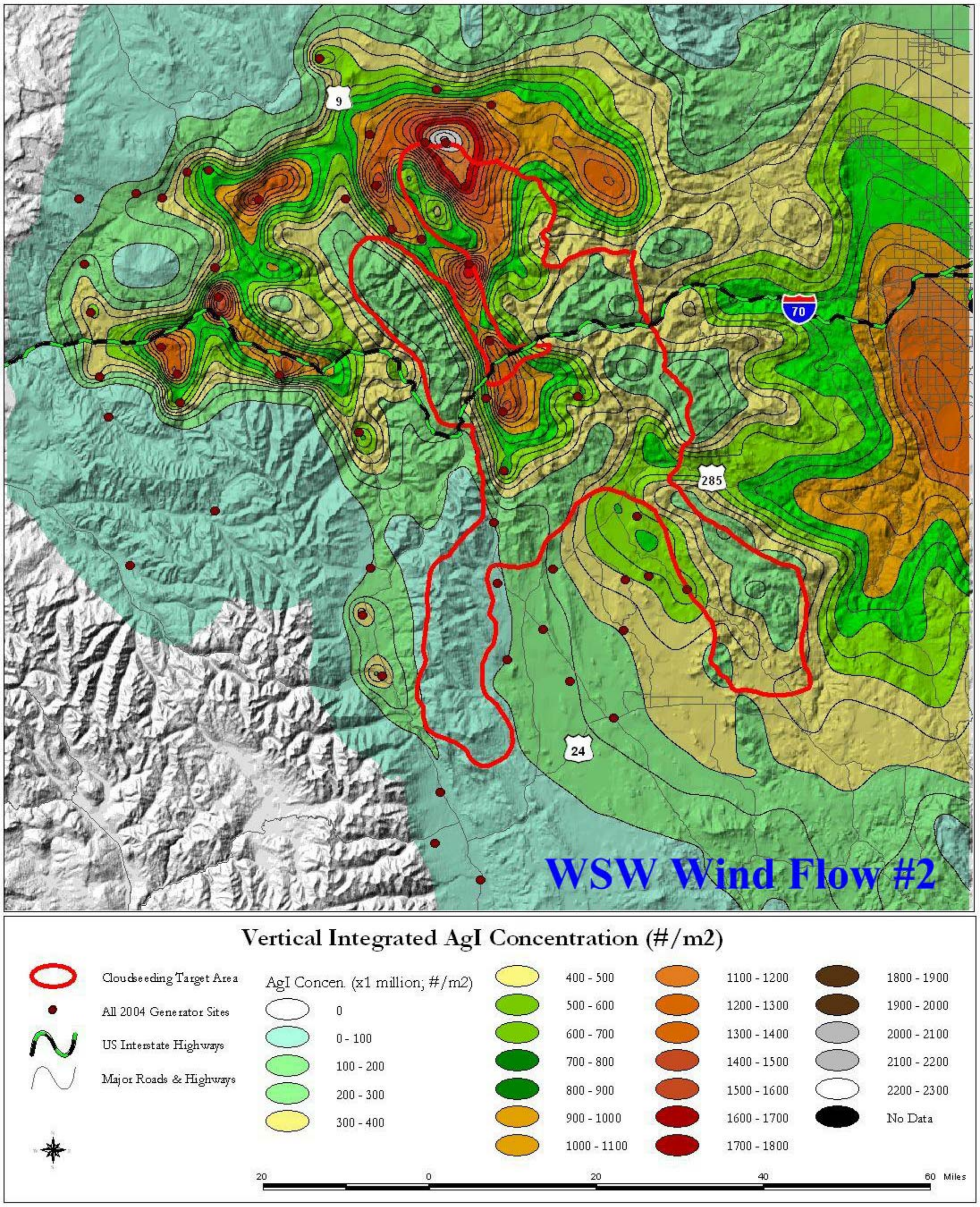


Figure 3.19. WSW Wind Flow Regime #2 – Model Simulated 28-hr Vertical Integrated AgI Concentration for 2100 MST on November 14, 2003

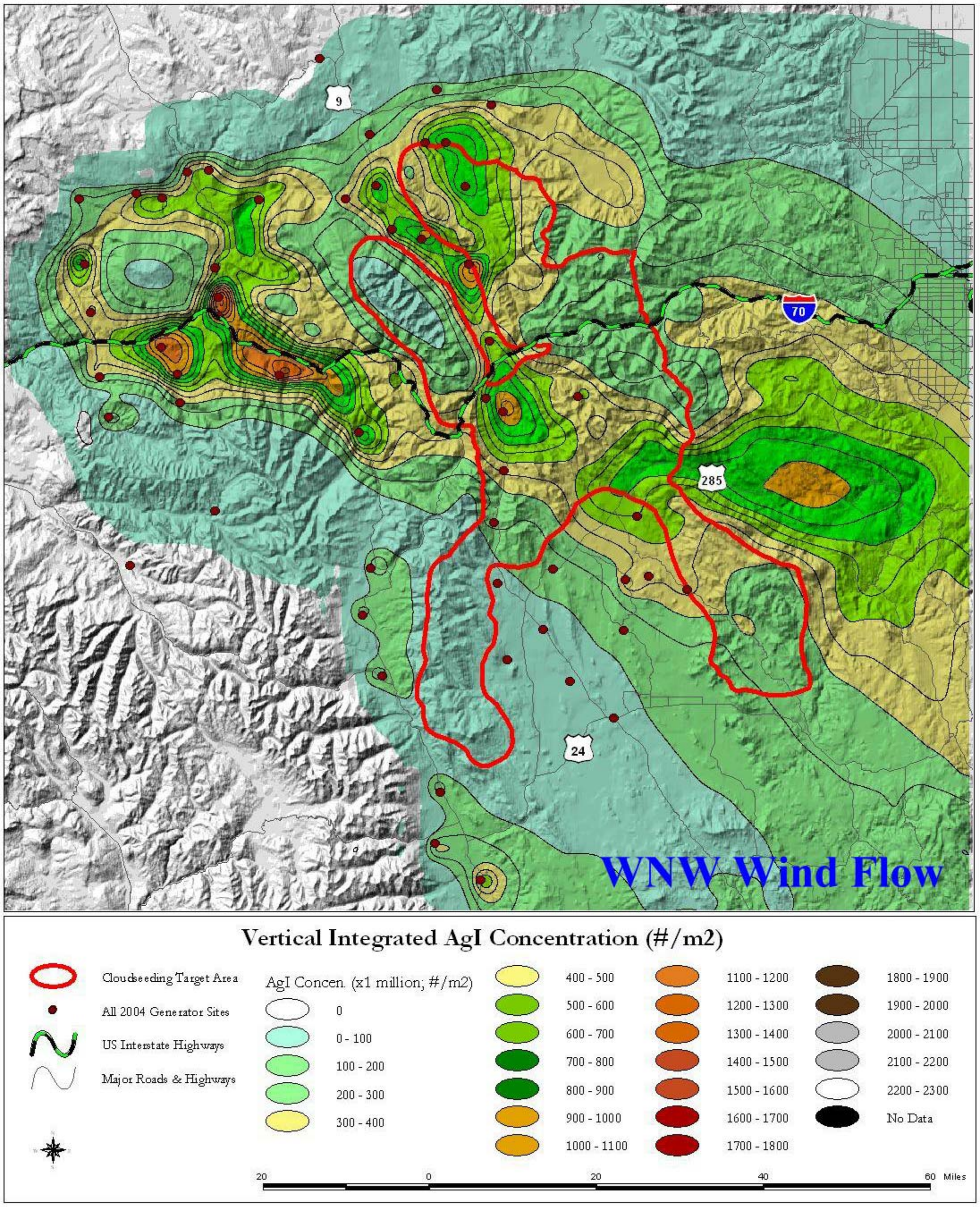


Figure 3.20. WNW Wind Flow Regime – Model Simulated
28-hr Vertical Integrated AgI Concentration
for 2100 MST on November 26, 2003

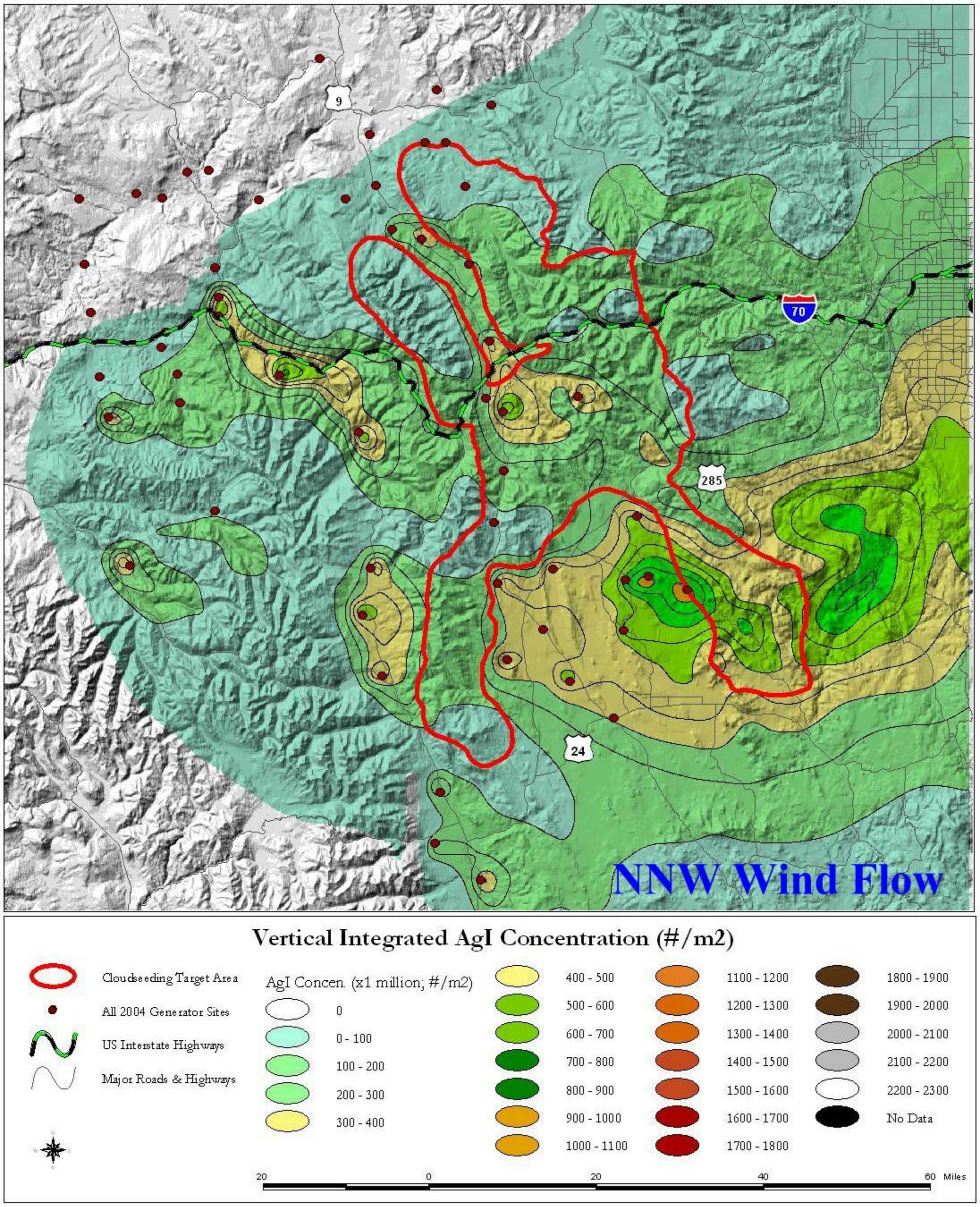


Figure 3.21. NNW Wind Flow Regime – Model Simulated
10-hr Vertical Integrated AgI Concentration
for 0300 MST on December 15, 2003

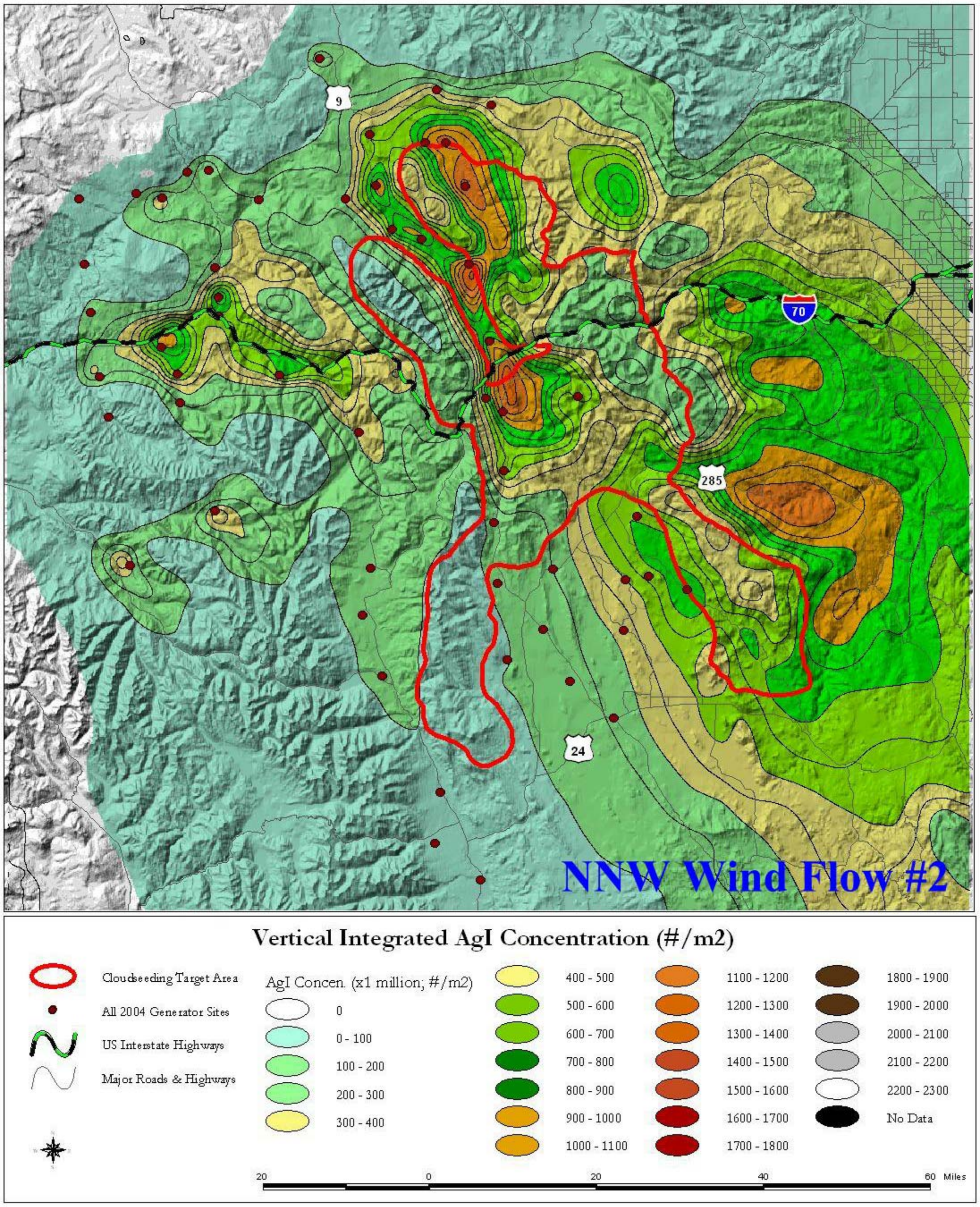


Figure 3.22. NNW Wind Flow Regime #2 – Model Simulated
10-hr Vertical Integrated AgI Concentration
for 0300 MST on February 5, 2004

3.5 Distribution and Change of Model SLW for Control and Seed Days

Project researches were puzzled that the model indicated that there was only limited or no SLW available for glaciation, and basically no seeding effects. It is well known by those in the Weather Modification community that AgI released in supercooled clouds makes ice crystals. So the fact that the model showed very little difference between seed and no-seed simulated precipitation (Subsection 3.3) suggests that there was essentially no SLW remaining in the model clouds when seeded, i.e., in the no-seed control runs the model overseeds itself. Also, the sensitivity tests (Subsection 3.4) showed that the vertically-integrated SLW in the model did not change significantly between the various background IFN concentration experiments.

The small amounts or non-existing SLW was evidenced by the fact that for 21 of the 30 selected days, the model no-seed control runs had no grid points with SLW over the target area. Based on the past experiences of project researchers in the Colorado mountains during the winter and aircraft icing studies, it is difficult to accept that there was essentially no SLW in the winter orographic clouds over the target area. This is a model problem that definitely needs further research. Note that we are looking at 2-hr samples so if SLW varies rapidly it could be a sampling issue.

Figures 3.23 – 3.28 show vertically integrated SLW on the RAMS Grid 3 for the six days selected for the Lagrangian case studies. It was desired to select map times with maximum vertically integrated SLW over the target area. If there was no SLW over the target area, then the researchers looked for times with some SLW on Grid 3. If there was no SLW, a time was selected. The hours given in the labels for the maps (e.g. 10-Hour) are the number of hours from the time and date of model initialization.

Figure 3.23 shows some SLW over the west-central and northeast portions of Grid 3, but no SLW over the target area. Figure 3.25 shows a small area of SLW along the west-edge of the northwest arm of the target area. Perhaps these areas of SLW were related to model simulated convective activity. Figures 3.24 and 3.26-3.28 show no vertically integrated SLW over the target area or anywhere within Grid 3.

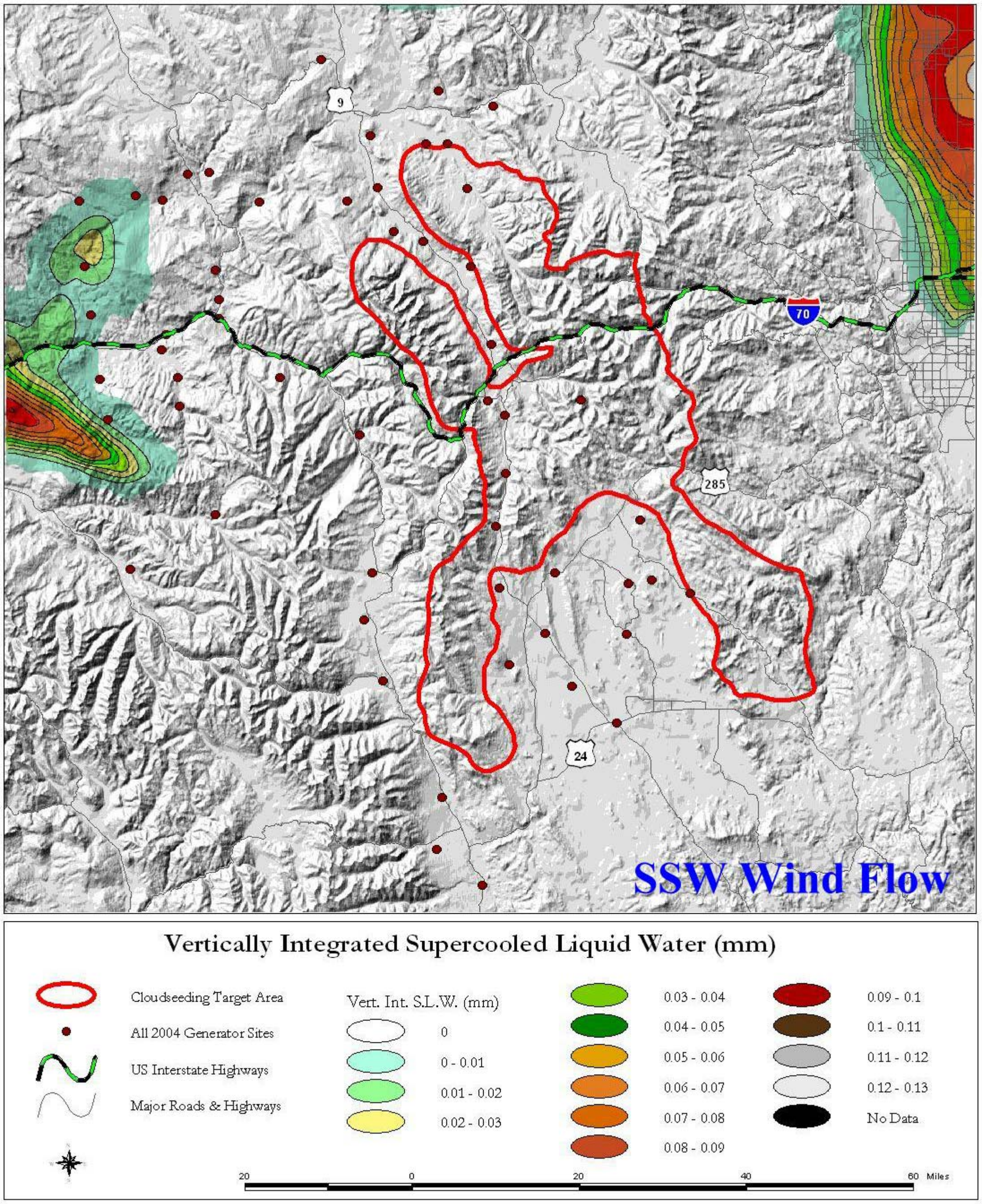


Figure 3.23. SSW Wind Flow Regime – Model Simulated 6-hr Vertical Integrated Supercooled Liquid Water for 2300 MST on November 2, 2003

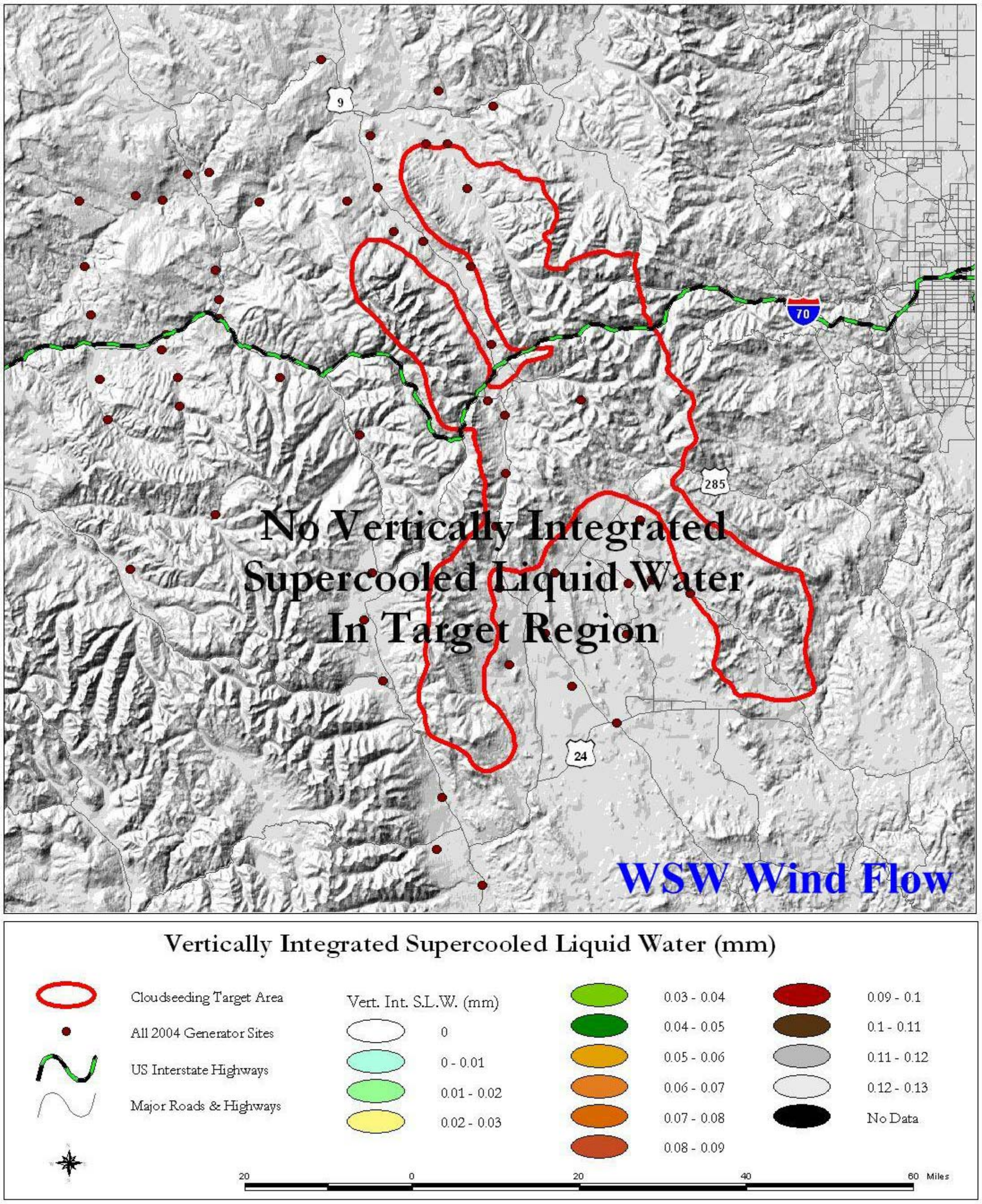


Figure 3.24. WSW Wind Flow Regime – Model Simulated 26-hr Vertical Integrated Supercooled Liquid Water for 1900 MST on January 2, 2004

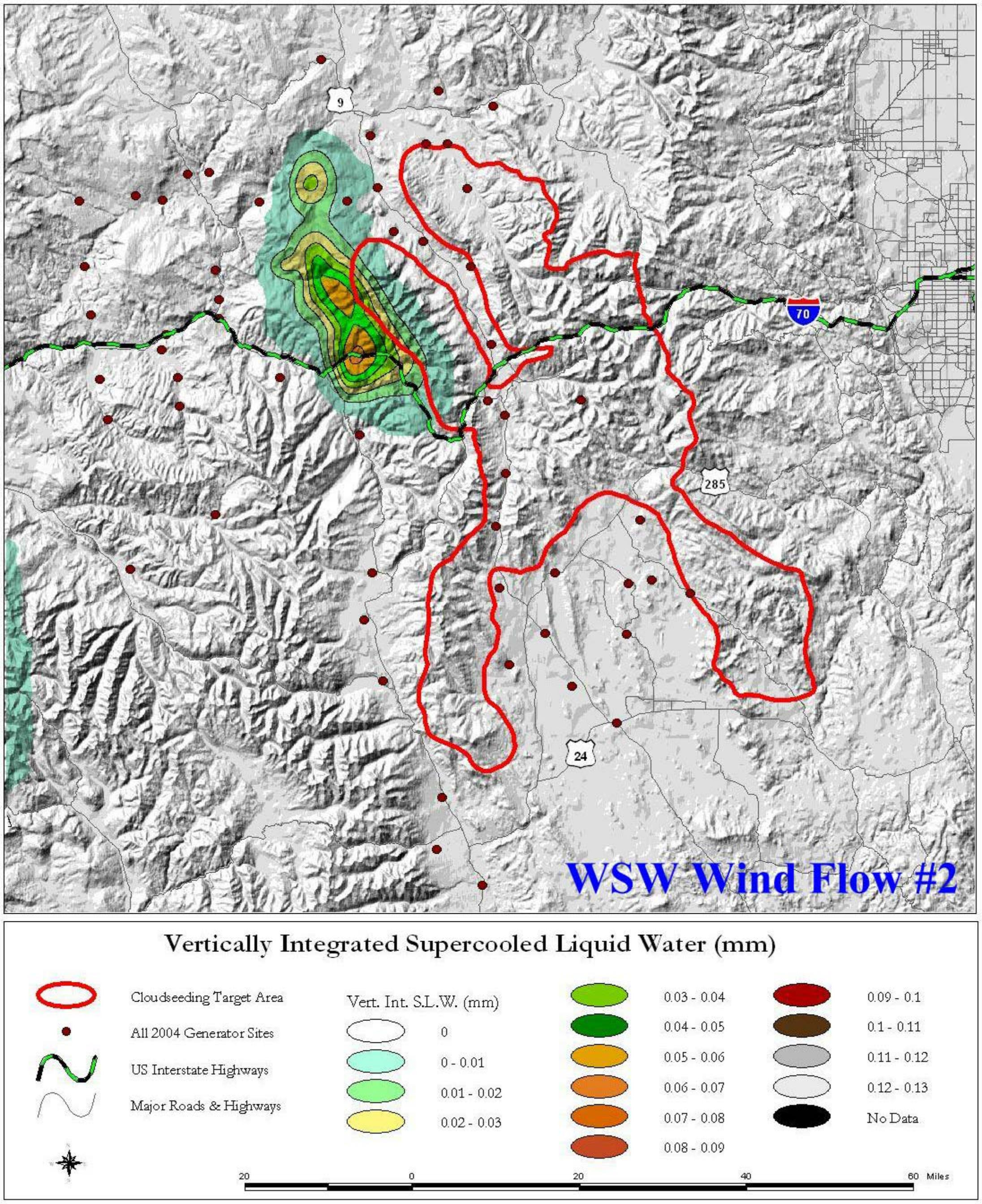


Figure 3.25. WSW Wind Flow Regime #2 – Model Simulated 4-hr Vertical Integrated Supercooled Liquid Water for 2100 MST on November 13, 2003

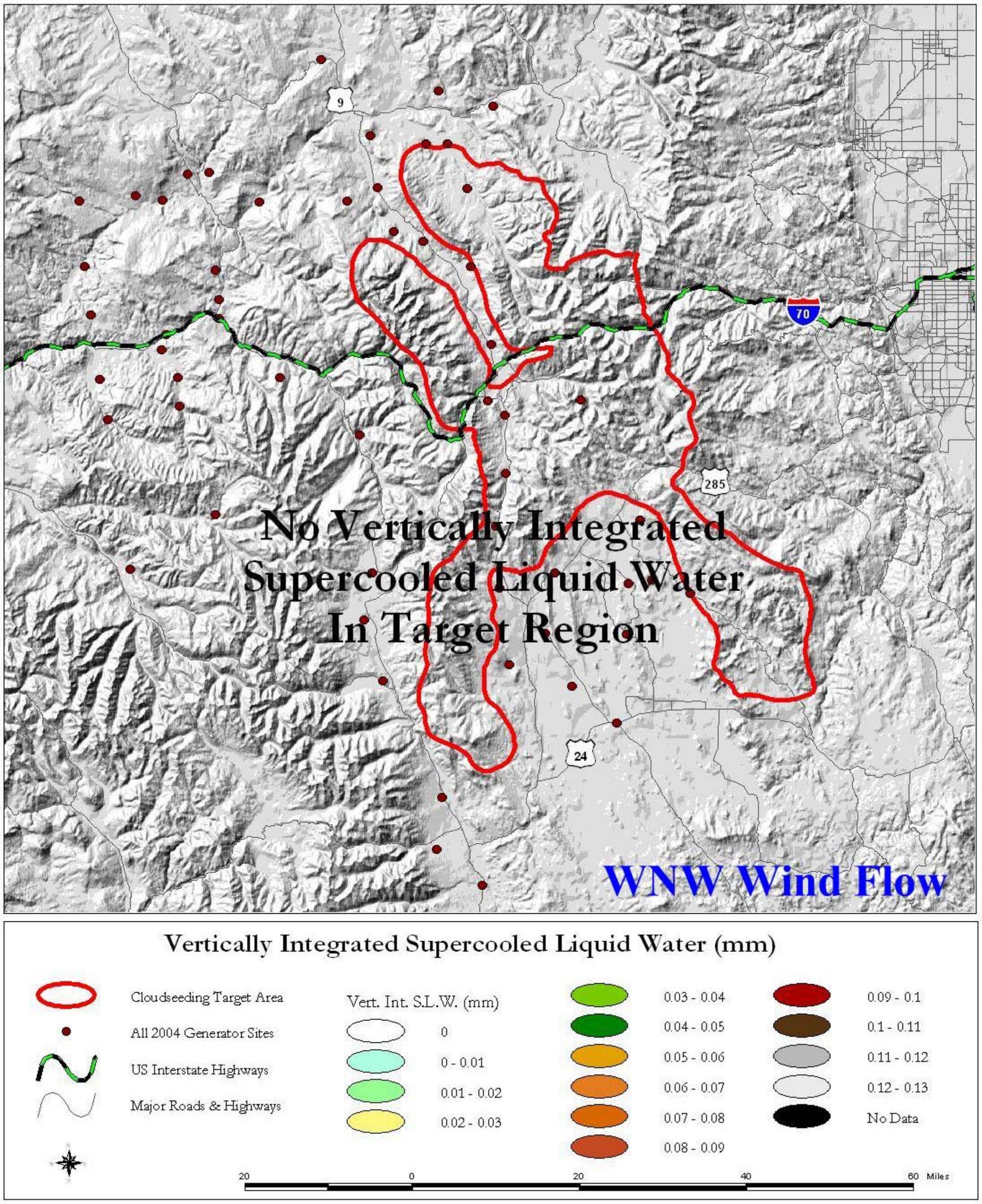


Figure 3.26. WNW Wind Flow Regime – Model Simulated
28-hr Vertical Integrated Supercooled Liquid Water
for 2100 MST on November 26, 2003

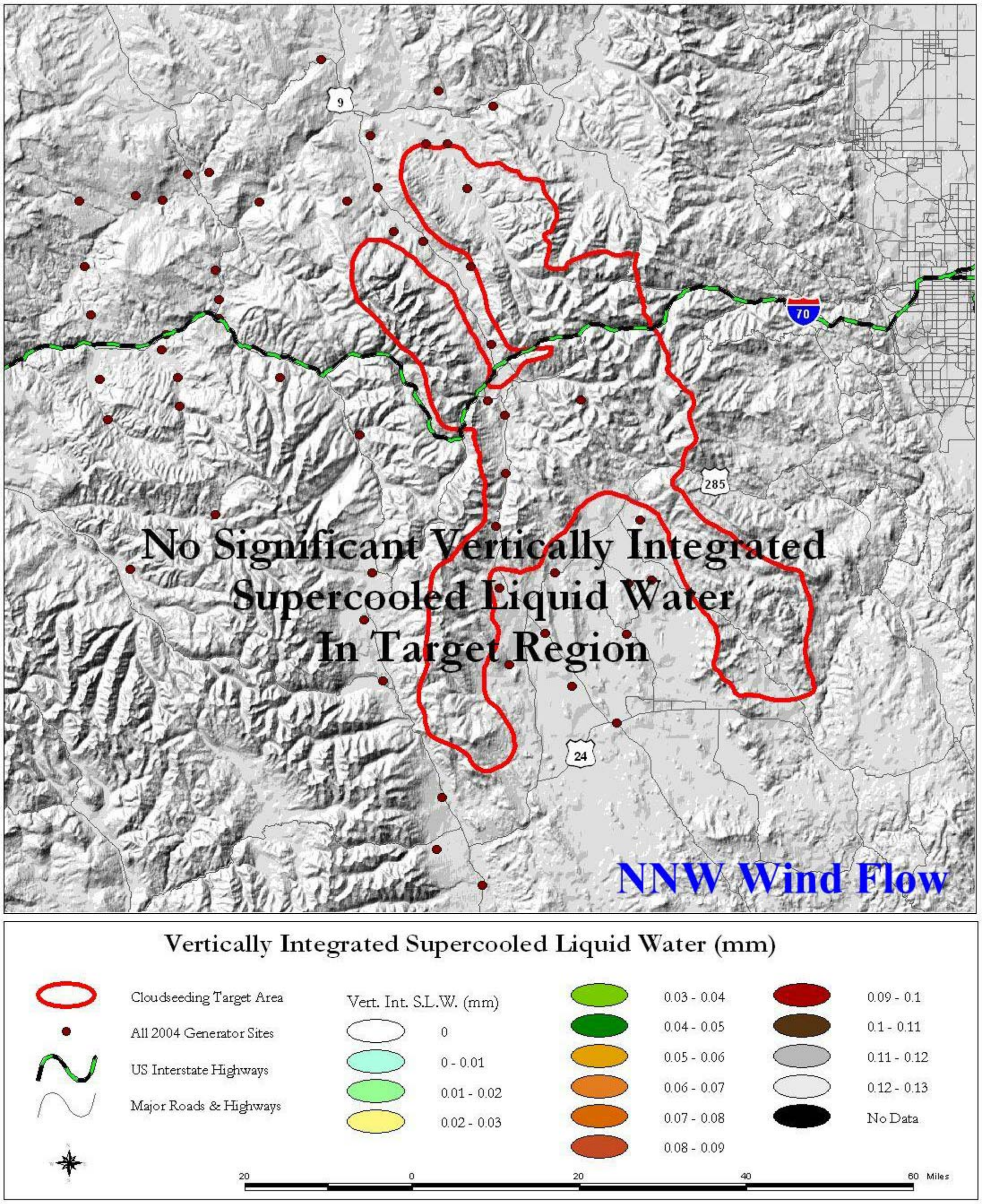


Figure 3.27. NNW Wind Flow Regime – Model Simulated
10--hr Vertical Integrated Supercooled Liquid Water
for 0300 MST on December 15, 2003

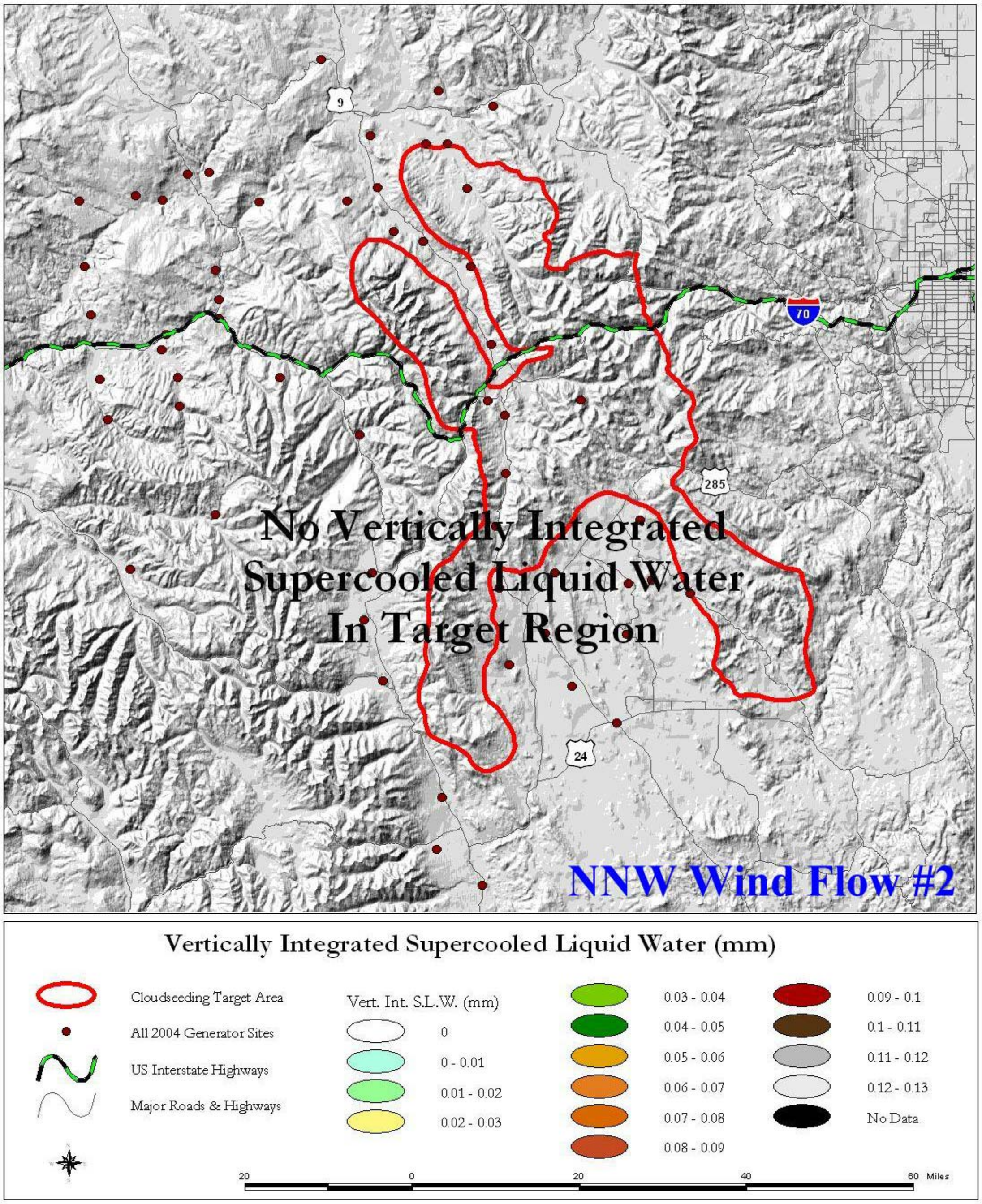


Figure 3.28. NNW Wind Flow Regime #2 – Model Simulated 10-hr Vertical Integrated Supercooled Liquid Water for 0300 MST on February 5, 2004

3.6 Comparison of Rawinsonde and Model Low-level Temperatures

Subsection 2.7 described three model problems that contributed to unrealistically warm low-level temperatures. Even after model fixes were implemented in mid-February 2004, there still appeared to be a low-level warm temperature bias. The Denver Water cloud seeding program's seeding contractor, Larry Hjermstad, noticed significant improvement in model forecast low-level temperatures after the fixes were made, but suspected that the model output 700-mb temperatures were still about 2°C too warm. He believed that the model was forecasting temperatures that were too warm in the low levels when the best moisture was available; consequently, the model retarded the activation efficiency because of the temperature activation curve from WWC generator tests build into the model.

In order to evaluate the magnitude of the model's warm temperature bias, Ray McAnelly from the CSU research team did two case studies comparing model forecast 700-mb level (about 10,000 feet MSL) temperatures with NWS 700-mb analyses where the temperatures were obtained from rawinsonde upper-air observations. Since the RAMS 3-km Grid 3 only has one NWS sounding station (Denver/DNR) on it, he used temperature analyses for the three sounding sites on the 12-km Grid 2 (Denver CO/DNR, Grand Junction CO/GJT, and Riverton WY/RIW). For better temperature precision, he used sounding data available from the University of Wyoming Web site: (http://weather.uwyo.edu/upperair/sounding.html).

Case 1: January 29, 2004 – 0000Z

This case was a WNW wind regime with cold advection at the 700-mb level. The NWS 700-mb analysis is shown in Figure 3.29. The corresponding RAMS model 24-hr forecast 700-mb level temperature and wind flow output from the control run (initialized at 040128.00) is shown in Figure 3.30. The three NWS sounding sites are marked (+) in this figure. The comparisons of temperature data for the three sites are listed in Table 3.5. The two soundings over Colorado show a warm temperature bias at the 700-mb level, with the greatest difference being +1.0°C at GJT to the west of the project area.

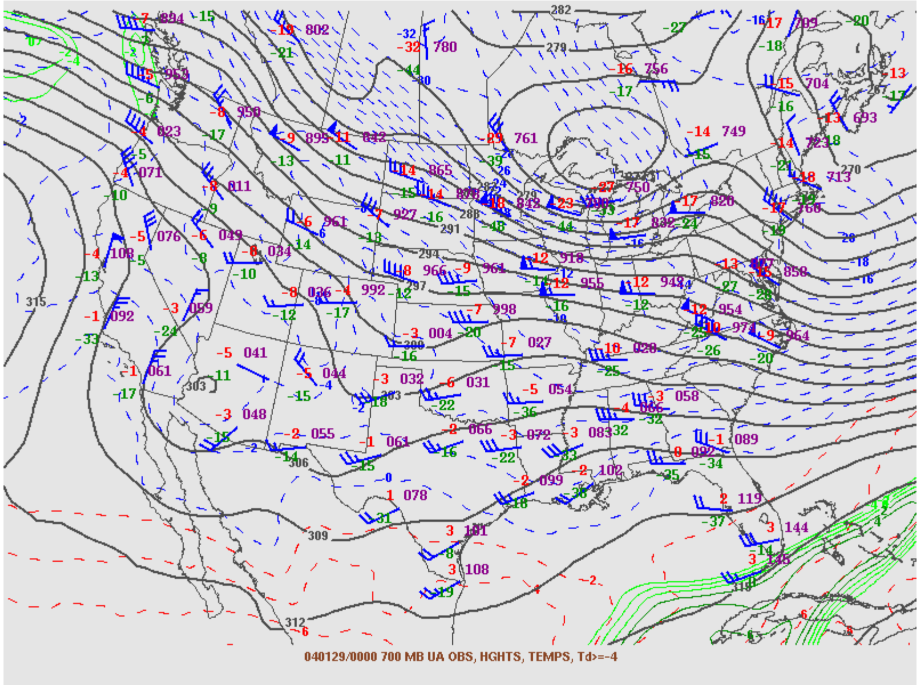
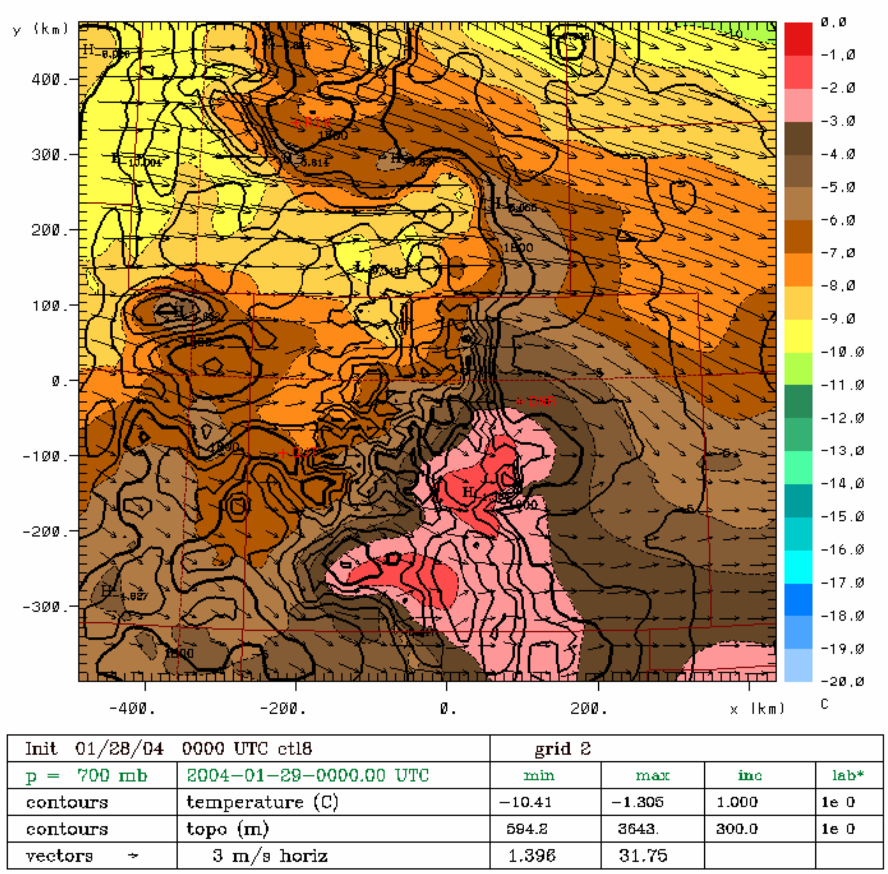


Figure 3.29. NWS 700-mb analysis for 0000Z January 29. 2004.



Init 01/28/04 0000 UTC ctl8		grid 2			
p = 700 mb	2004-01-29-0000.00 UTC	min	max	inc	lab*
contours	temperature (C)	-10.41	-1.305	1.000	1e 0
contours	topo (m)	594.2	3643.	300.0	1e 0
vectors →	3 m/s horiz	1.396	31.75		

Figure 3.30. RAMS Grid 2 temperature analysis for 0000Z January 29, 2004.

Table 3.5. Case 1 Comparison of Rawinsonde and RAMS 700-mb temperatures

Sounding site	Sounding Temp.	Model Forecast	RAMS-Observed
DNR	-3.7°C	-3.3°C	+0.4°C
GJT	-7.7°C	-6.7°C	+1.0°C
RIW	-6.1°C	-6.7°C	-0.6°C

Case 2: February 05, 2004 – 0000Z

This case was a cold NNW wind regime at the 700-mb level. The NWS 700-mb analysis is shown in Figure 3.31. This NWS analysis shows a closed low pressure area located over Colorado. The corresponding RAMS Grid 2 model 24-hr forecast 700-mb level temperature and wind flow output from the control run (initialized at 040205.00) is shown in Figure 3.32. The coldest temperatures are to the north of Grid 3 with the wind flow toward the Denver Water project area in Colorado. The three NWS sounding sites are marked (+) in this figure. The comparisons of data for the three sites are listed in Table 3.6. All three soundings show a warm temperature bias at the 700-mb level. The average model bias for the three sounding sites was about +1.8°C, with the greatest difference being +2.0°C at DNR to the east of the project area. The warm temperature bias for the colder Case 2 was about 1°C worse than in Case 1.

Table 3.6. Case 2 Comparison of Rawinsonde and RAMS 700-mb temperatures

Sounding site	Sounding Temp.	Model Forecast	RAMS-Observed
DNR	-12.3°C	-10.3°C	+2.0°C
GJT	-10.9°C	-9.3°C	+1.6°C
RIW	-9.9°C	-8.8°C	+1.9°C

The two case studies confirmed that the real-time model forecasts continued to have a low-level warm temperature bias after the model fixes were implemented in mid-February 2004. This low-level warm temperature bias is important to the evaluation of the Colorado WDMP project, because such a bias delays IN activation, crystal growth and fallout. The consequence could be errors in estimated precipitation over the Denver Water cloud seeding project's target area.

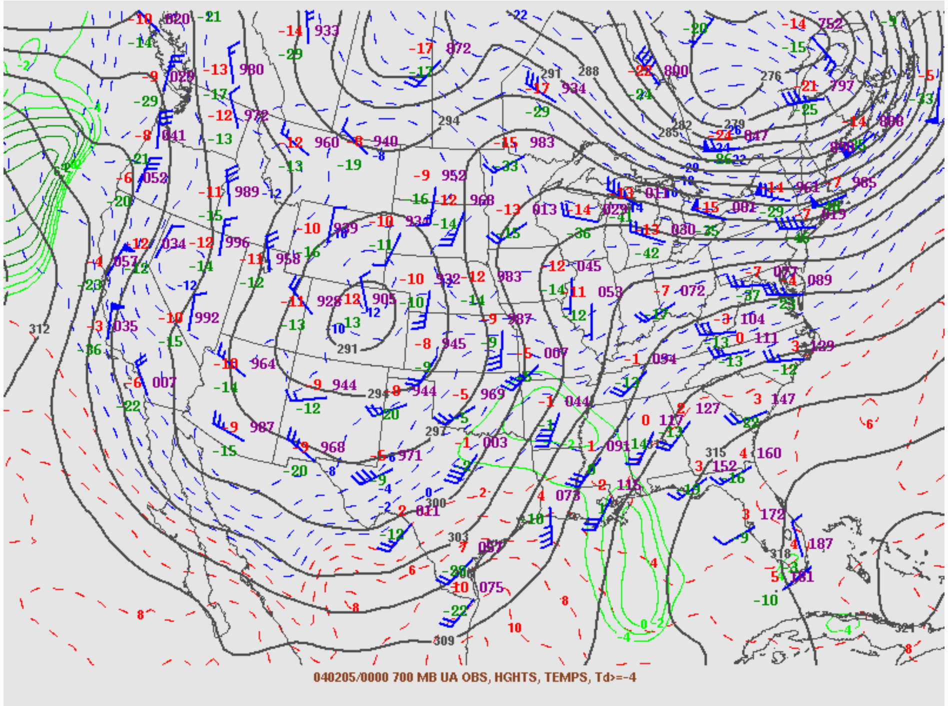
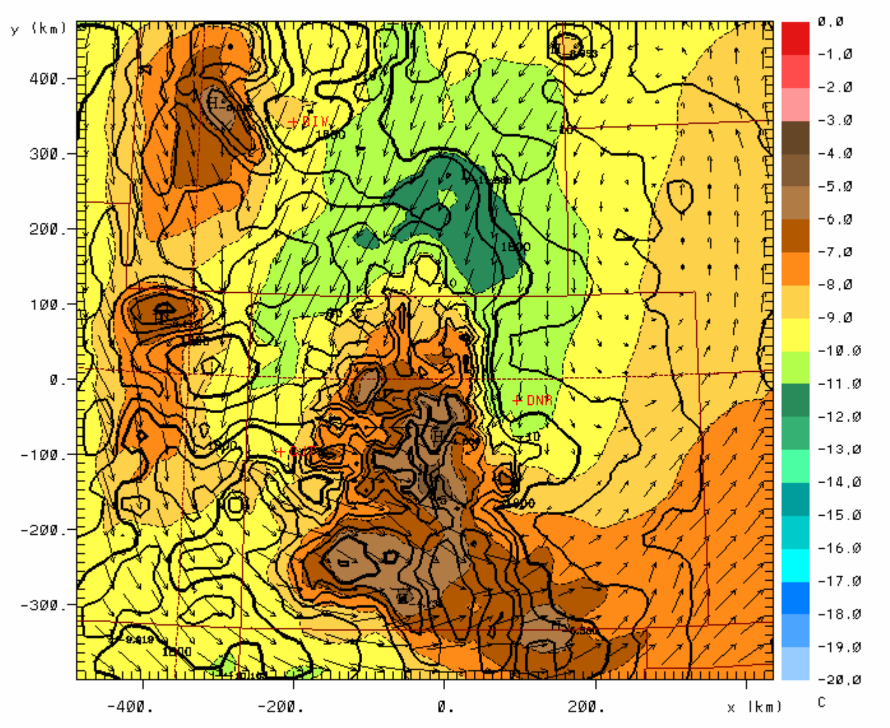


Figure 3.31. NWS 700-mb analysis for 0000Z February 5, 2004.



Init 02/04/04 0000 UTC ctl8		grid 2			
p = 700 mb	2004–02–05–0000.00 UTC	min	max	inc	lab*
contours	temperature (C)	−11.59	−4.567	1.000	1e 0
contours	topo (m)	594.2	3643.	300.0	1e 0
vectors →	3 m/s horiz	0.2325	19.16		

Figure 3.32. RAMS Grid 2 temperature analysis for 0000Z February 5, 2004.

3.7 MRBP Evaluation of Model Performance

The setting up of Multivariate Randomized Block Permutation (MRBP) statistics for evaluating model skill for simulated precipitation was described in Subsection 2.9. This evaluation focused on the 30 selected cloud seeding days listed in Table 2.2. The 24-hr SNOTEL accumulated precipitation data were used in the evaluation.

The research staff at CSU selected 30 SNOTEL sites to use in the MRBP evaluation. These 30 sites are highlighted in yellow in Appendix 3. The selected sites were grouped geographically and located both within and outside of the target area. Appendix 6 includes a map of the groupings of the selected SNOTEL sites. This appendix also lists the SNOTEL 30-day observed precipitation and a model 30-day control (no-seed) simulated precipitation for each of the 30 sites.

The model control simulations were initialized at 0000 UTC each day and were run out through at least 32 hours. The fields of 24-hr simulated precipitation were derived by subtracting the accumulated precipitation 8 hours into the run from that at 32 hours into the run, corresponding to the 0800 to 0800 UTC (0100 to 0100 MST) period of the SNOTEL observations. For comparison with the SNOTEL observations, 24-hr control run simulated precipitation was extracted by bilinear interpolation at the SNOTEL locations from the four nearest model grid points.

The MRBP evaluation consisted of 3 sets of analyses, where each pair consisted of an observed vs. control (no-seed) run analysis and a corresponding observed vs. seeded run analysis:

Set 1: All 30 SNOTEL sites (12 in target area, 18 in non-target area)
Set 2: 12 SNOTEL sites in the target area only
Set 3: 18 SNOTEL sites in the non-target area only

In each MRBP analysis, there were 4 experiments in which some of the controlling parameters were varied amongst reasonable ranges of values. These variations were the same for all the MRBP analyses.

The results from the 3 sets of MRBP analyses are listed in Appendix 6. Table 3.7 is an extracted summary of the MRBP analyses, in terms of two parameters: Agreement Measure (the larger the better) and P-Value (probability level – the smaller the better). The results from the evaluation show that the model is describing the non-seeded and seeded simulation equally well. Since the model simulated no-seed and seed simulated 24-hr precipitation values over Grid 3 were essentially the same, this finding was expected. While the signal of the fits is strong (all P-values about 1.0E-6 or less), the agreement measures are not outstanding (all fall between 0.18 and 0.26).

Table 3.7. Results of MRBP Analysis

Based on observed 24-hr precipitation at 30 SNOTEL sites, and simulated 24-hr precipitation in control (no-seed) and seeded runs at the same 30 sites, for the 30 selected seeding days.

SET 1: 30 SNOTEL Sites (12 in Target Area, 18 in Non-Target Area)

	Obs vs. No-Seed Run	Obs vs. Seeded Run
AGREEMENT MEASURE		
Experiment 1	0.2422708	0.2425952
Experiment 2	0.2514381	0.2543687
Experiment 3	0.1851506	0.1854308
Experiment 4	0.2177159	0.2204723
P-VALUE		
Experiment 1	0.1061620E-05	0.1000465E-05
Experiment 2	0.1911016E-07	0.1781136E-07
Experiment 3	0.5668024E-07	0.5687684E-07
Experiment 4	0.6535702E-07	0.6450544E-07

SET 2: 12 SNOTEL Sites (all in Target Area)

	Obs vs. No-Seed Run	Obs vs. Seeded Run
AGREEMENT MEASURE		
Experiment 1	0.2307681	0.2307067
Experiment 2	0.1757072	0.1789004
Experiment 3	0.1577664	0.1588549
Experiment 4	0.1806818	0.1830907
P-VALUE		
Experiment 1	0.1605811E-03	0.1607391E-03
Experiment 2	0.1385117E-03	0.1421757E-03
Experiment 3	0.8078840E-04	0.7761994E-04
Experiment 4	0.8011404E-04	0.8261498E-04

SET 3: 18 SNOTEL Sites (all in Non-Target Area)

	Obs vs. No-Seed Run	Obs vs. Seeded Run
AGREEMENT MEASURE		
Experiment 1	0.2476196	0.2493229
Experiment 2	0.2879500	0.2904346
Experiment 3	0.1962158	0.1966897
Experiment 4	0.2440450	0.2471194
P-VALUE		
Experiment 1	0.7568070E-05	0.6612415E-05
Experiment 2	0.8730154E-07	0.7678781E-07
Experiment 3	0.5254047E-06	0.5255164E-06
Experiment 4	0.3337998E-06	0.3164337E-06

3.8 Lagrangian Model Simulation Transport and Dispersion Case Studies

The CSU research team selected six of the 30 days for Lagrangian model simulation transport and dispersion case studies. The six case study days were selected from among the "best" wind regime classifications in the 30 selected days in Table 2.2. There are 16 such "best" cases among the 30 selected days in Table 2.2. CSU eliminated consideration of any changing wind regime due to low pressure trough passage (tropa) or approaching the target area (trof apch), because any changing wind regime would complicate analysis and interpretation, compared to the more steady, single directional classifications. From the remaining "best" single directional cases CSU attempted to select six that represented the wind regimes from SSW to NNW. The cases selected were representative of relatively light to heavy precipitation events, while avoiding consecutive or nearly-consecutive days (like the 01/02/2004 and 01/03/2004 WSW cases) because they might not be totally independent regimes. The six days selected are highlighted in yellow in Table 3.1.

The particle dispersion model utilized for this research was developed by Uliasz et al. (1996). The meteorological input to the model was provided by special RAMS forecast simulations for the six cases. These simulations were nearly identical to the final control runs described in Section 2.8, with two exceptions. First, a different vertical diffusion parameterization, utilizing a predictive turbulent kinetic energy (TKE) field, was used because of the need for the TKE variable in the particle dispersion model. Second, more frequent meteorological input was required than the 2-hr data archived for the control runs; thus 5-min data were saved in these extra runs. These simulations were initialized at 0000 UTC on the case study date and run through 36 hr to 1200 UTC on the following day. Precipitation and meteorological evolution in these runs matched the control simulations very closely.

The particle model requires a specification of particle sources and release rates, and calculates forward trajectories for all particles released. It was computationally and logistically prohibitive to specify sources corresponding to all 56 operational seeding generators, or to rigorously search for optimum generator placement through various hypothetical generator network scenarios. Instead, a representative subsample of 16 sites out of the 56 generators was used, as indicated in Figure 3.33 and Table 3.8. There are four geographical groupings, each with four generator sites. Groups 1 through 4 are located, respectively, to the southwest, west-northwest, north, and south of the target area, so that prevailing winds from those directions would presumably be most optimum in delivering seeded material from each respective group to the target area. In each group, the numerical identifiers for the generator sites are generally sequenced from high to low elevation.

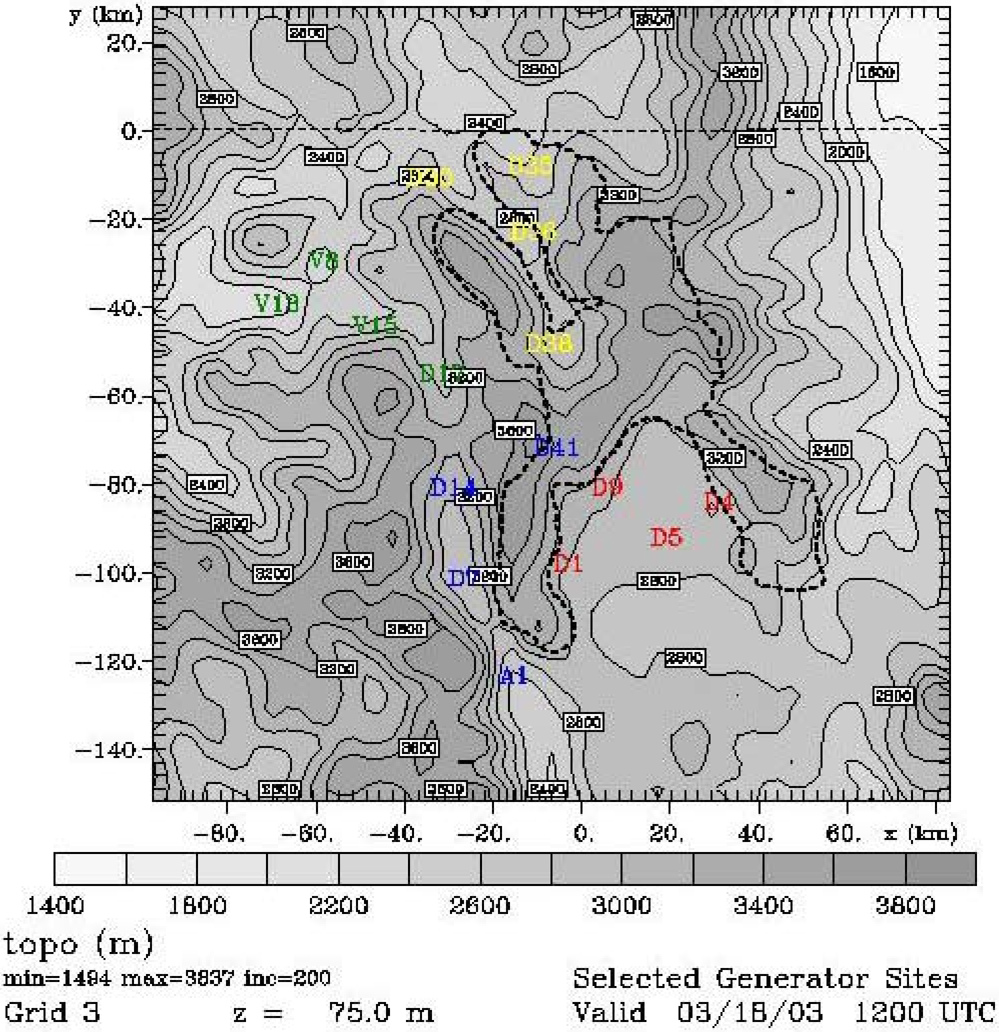


Figure 3.33. Locations of the 16-sites/4-groups used in the Lagrangian studies. (Group 1 in blue, Group 2 in green, Group 3 in yellow, Group 4 in red)

Table 3.8. Generator Sites Used in Lagrangian Analysis

Group 1 - Southwestern generators: Hoosier Pass/Arkansas Valley

N	ID	Latitude	Longitude	Elevation (m) GPS	Model	Site Name
1	D41	39.35500	-106.06500	3381	3565	Hoosier Pass
2	D14	39.27400	-106.33500	3017	3043	Leadville
3	D7	39.09000	-106.30666	2947	2889	Twin Lakes
4	A1	38.89283	-106.17583	2523	2597	3 Elk Creek

Group 2 – West-Northwestern generators: Eagle Valley

N	ID	Latitude	Longitude	Elevation (m) GPS	Model	Site Name
5	D17	39.50733	-106.36633	2646	2978	Redcliff
6	V15	39.60266	-106.54300	2908	2661	Beaver Creek
7	V8	39.73383	-106.68083	2205	2306	4 Eagle Ranch
8	V13	39.64633	-106.80417	2108	2136	Crystal Lakes

Group 3 - Northern generators: Blue/Williams Fork Valleys

N	ID	Latitude	Longitude	Elevation (m) GPS	Model	Site Name
9	D38	39.56800	-106.08667	2773	2943	Frisco
10	D36	39.79583	-106.12783	2605	2759	Big Gulch
11	D30	39.90517	-106.40183	2747	2788	Spring Creek
12	D35	39.92883	-106.13667	2573	2625	Lost Creek

Group 4 - Southern generators: South Park

N	ID	Latitude	Longitude	Elevation (m) GPS	Model	Site Name
13	D1	39.11967	-106.03333	2925	2991	Round Hill
14	D9	39.27667	-105.93350	2921	3047	Red Hill Pass
15	D5	39.17250	-105.77717	2920	2900	Ruby Gulch
16	D4	39.24434	-105.63934	2715	2832	Eagle Rock Ranch

Each of the 16 sites is a particle source at 1 m above the ground in the model, releasing 1 particle per second throughout the 36-hr run. Thus each source produces 3600 particles per hour, for a total of 5.76×10^4 particles released per hour by the entire 16-site network. The particle model calculated particle locations with a 20-sec forward timestep, and particle location files were saved at 15-min intervals. With a transport speed of 10 m/s, a particle moves 9 km during this interval, which is too coarse for displaying and interpreting individual trajectories. Instead, 15-min particle concentration fields were calculated for each source based on the 15-min particle location files. These concentration fields use the same 3-km horizontal grid structure as the RAMS fine grid and a 500 m vertical grid cell depth. Concentration fields were smoothed by averaging over five consecutive 15-min analysis times, and were examined at 2-hr intervals.

Figures 3.34-3.39 show the 0.0 to 2.0 km AGL concentrations at a selected time for each of the six Lagrangian case studies, proceeding in the same sequence of SSW through NNW wind regimes used in Subsections 3.2-3.5. The times chosen are representative of an extended period of relatively steady wind flow that characterizes the regime. Concentrations are summed and color-contoured for each group of four sources (Figure 3.33, Table 3.8). A small local maximum is generally centered over and clearly identifies each source (to avoid clutter, the numeric identifiers from Table 3.8 are offset by 6 km to the west of their respective generator sites). An axis of higher concentration generally extends in the prevailing downwind direction of the respective wind regime, marking a plume from each source.

In general, the particle concentration fields are reasonably consistent with the advection and transport of the scalar fields for simulated AgI in the seeding runs discussed in Section 3.4. Direct comparisons are difficult because of the time and generator dependent release of seeded material in the seeding runs based on the seeding logs, versus the constant release rate for all 16 sites used for the particle model. Note that the times of the vertically-integrated AgI concentration maps for the six cases in Figures 3.17-3.22 were selected at the time of maximum total AgI in the entire domain. They generally do not fall within the extended period of relatively steady winds from which the particle concentration fields were selected in Figures 3.34-3.39 and which characterize the wind regime.

For instance, the seeding contractor designated a "targeting wind” of 240-270 degrees for Nov. 14, 2003 and designated it as a WSW wind regime. However, the WSW winds occurred early on Nov. 14, turned westerly, and then west-northwesterly as the system moved through Colorado. The particle concentration field for this case in Figure 3.36 is at 1400 UTC on 14 Nov, after the WSW phase had turned westerly, and thus the particle plumes are generally toward the east. However, the scalar concentration field in Figure 3.19 is at 28 hr into the run or at 0400 UTC on 15 Nov, well after the winds had turned WNW, and thus the southeastward directed plumes seen there are realistic, but inconsistent with the WSW designation of the event.

One case for which the times are similar and both within the extended steady wind period is for the WNW regime for Nov. 26, 2003, where the scalar concentration field at 28 hr into the simulation in Figure 3.20 is only 4 hr later than the particle concentration field in Figure 3.37. A number of matching plumes can be seen in the two figures, particularly from the more active generator sites in the northwestern and northern portions of Figure 3.20 (groups 2 and 3 in Figure 3.37).

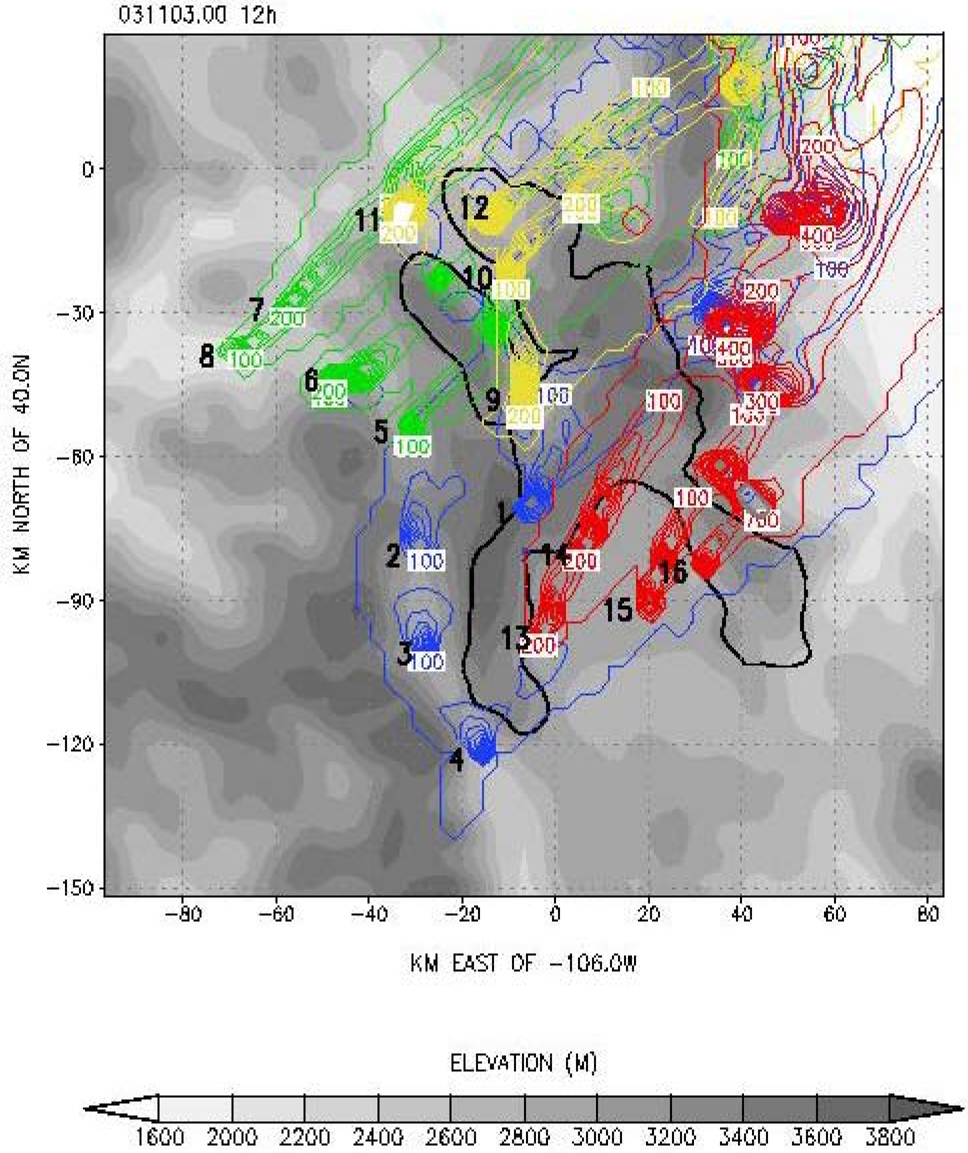


Figure 3.34. Particle concentration fields (0-2 km AGL) for the Nov. 3, 2003 SSW regime at hour 12 (0500 MST)

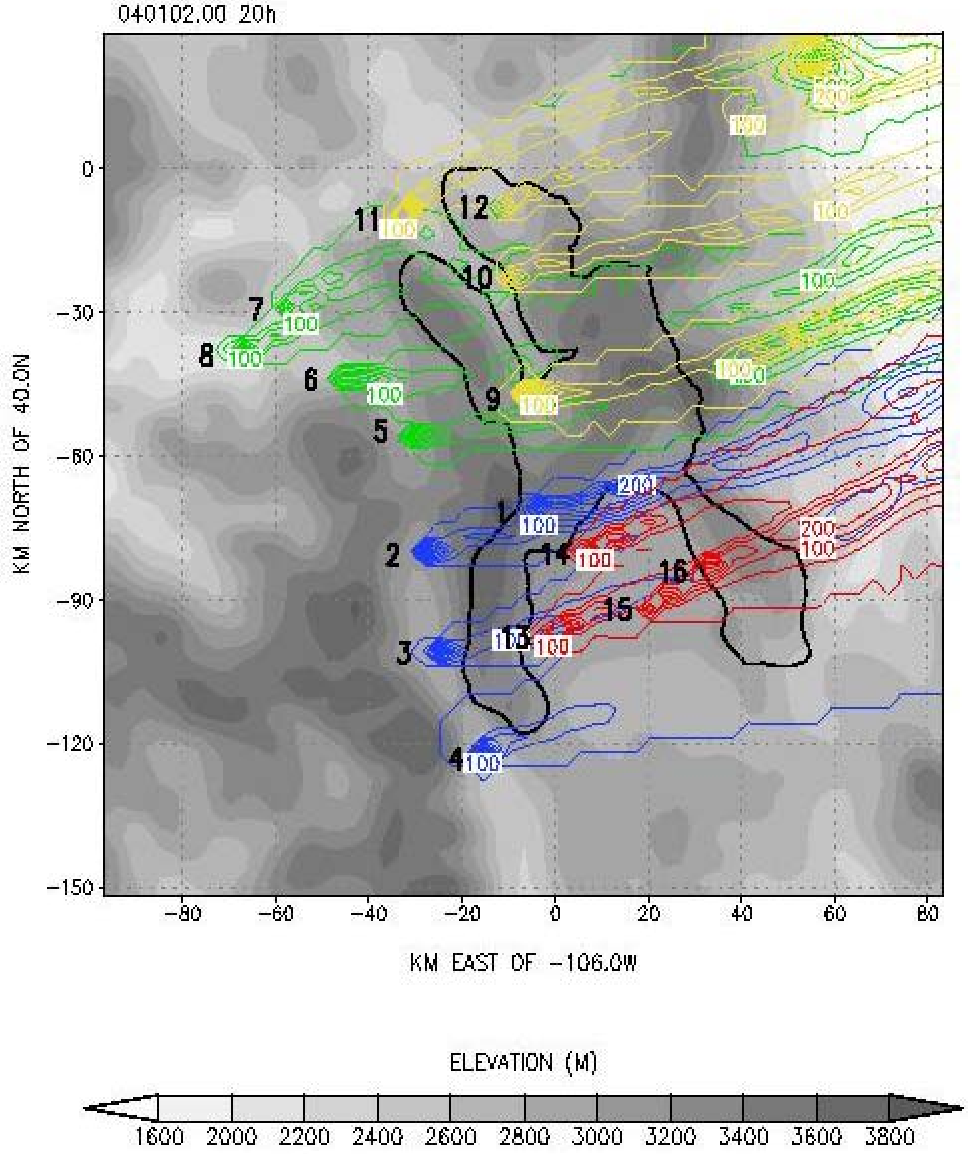


Figure 3.35. Particle concentration fields (0-2 km AGL) for the Jan. 2, 2004 WSW regime at hour 20 (1300 MST)

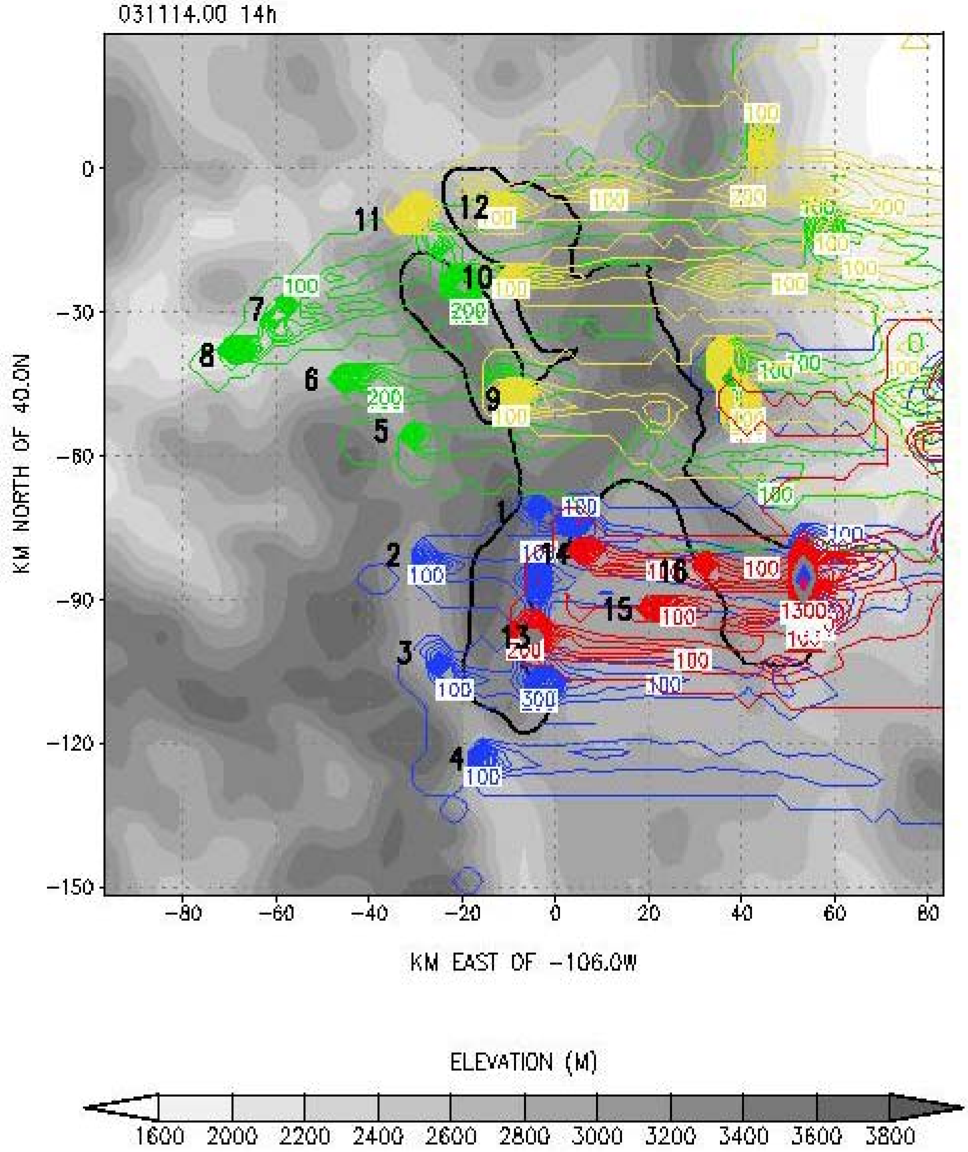


Figure 3.36. Particle concentration fields (0-2 km AGL) for the Nov. 14, 2003 WSW regime #2 at hour 14 (0700 MST)

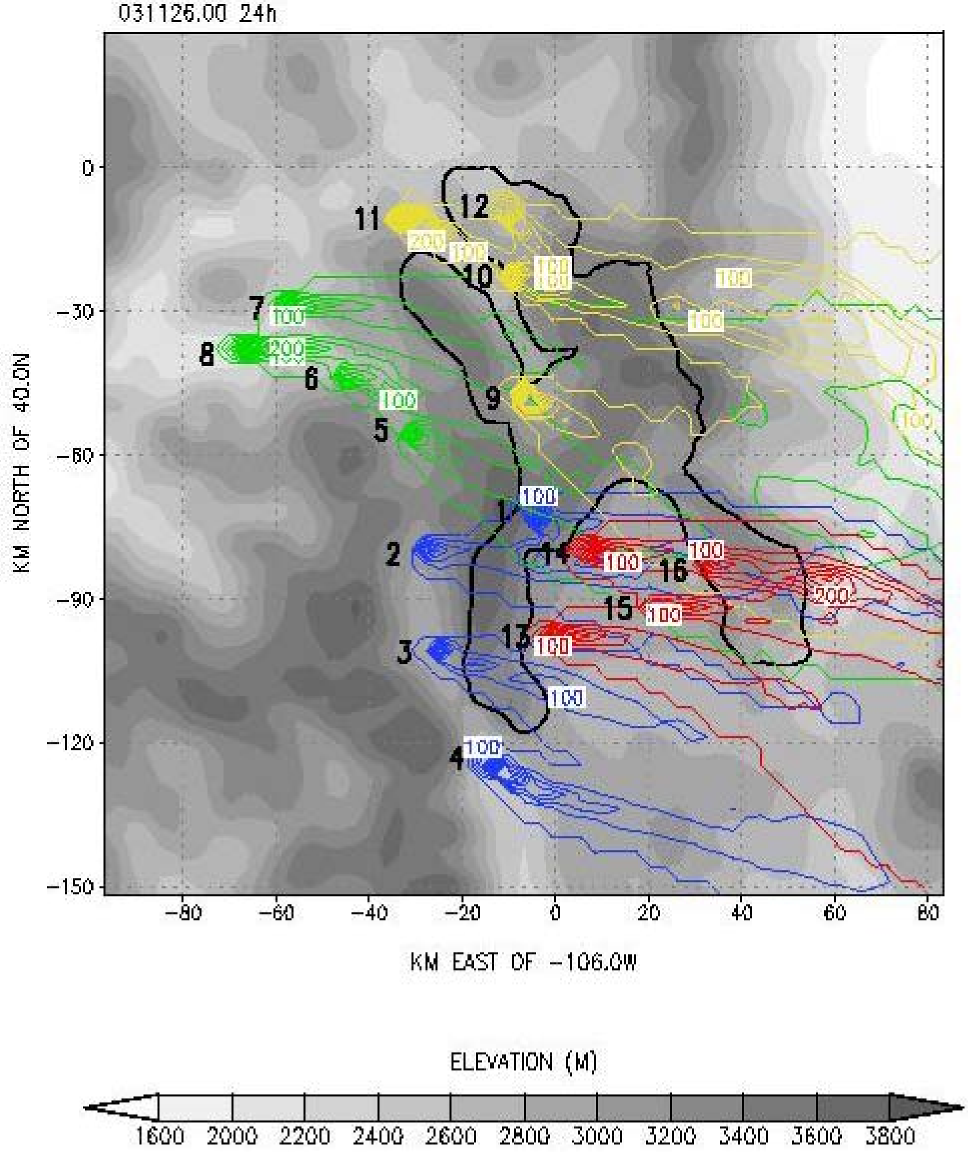


Figure 3.37. Particle concentration fields (0-2 km AGL) for the Nov. 26, 2003 WNW regime at hour 24 (1700 MST)

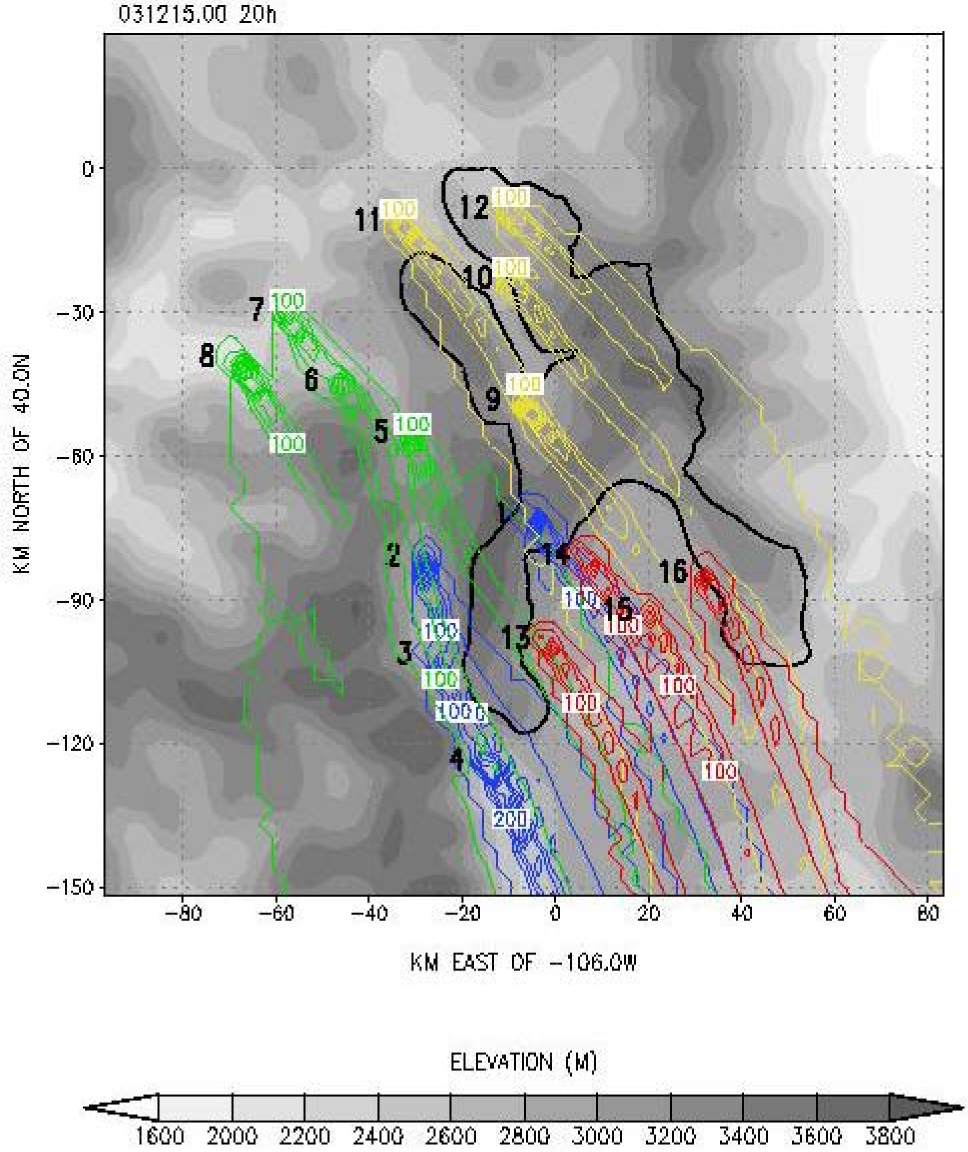


Figure 3.38. Particle concentration fields (0-2 km AGL) for the Dec.15, 2003 NNW regime at hour 20 (1300 MST)

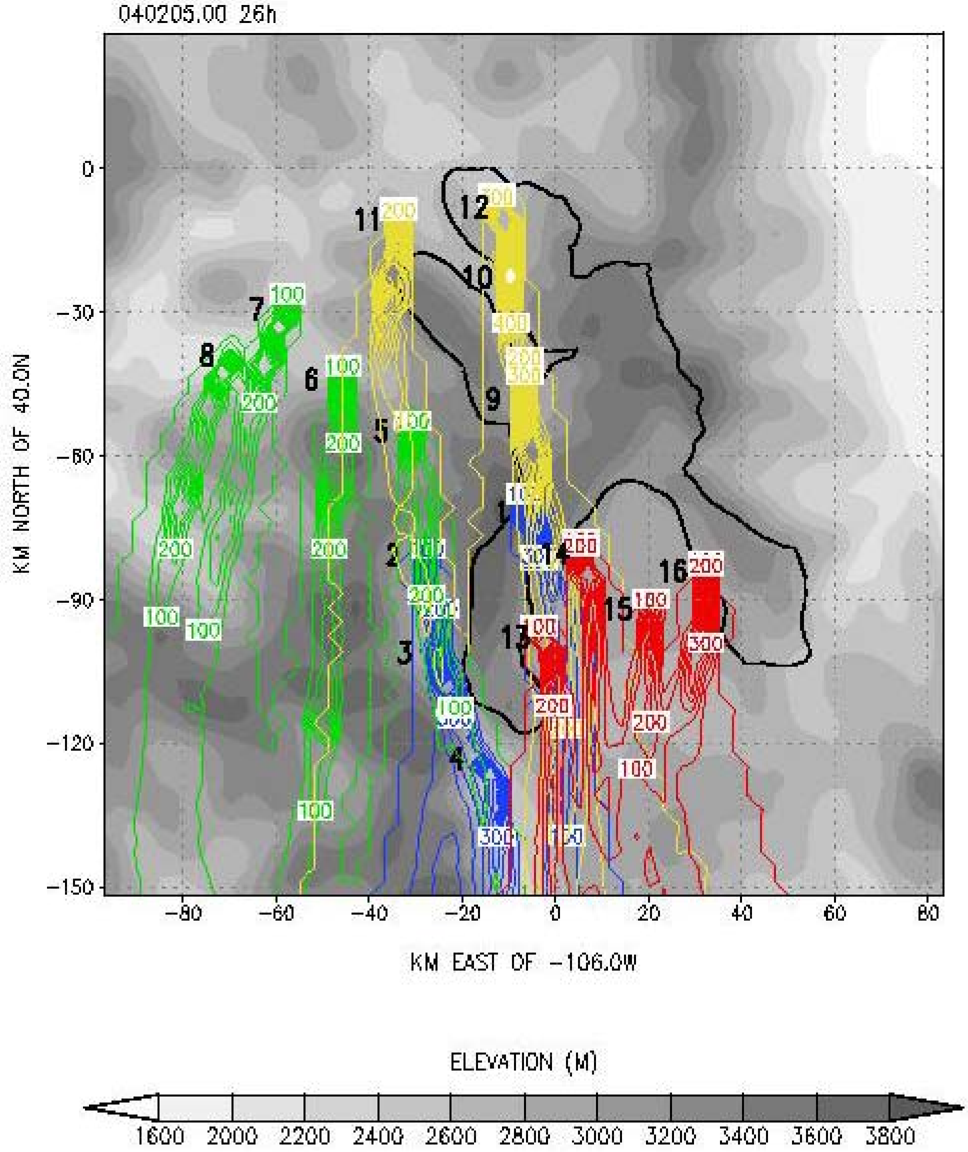


Figure 3.39. Particle concentration fields (0-2 km AGL) for the Feb. 5, 2004 NNW regime #2 at hour 26 (1900 MST)

A more extensive time by time comparison of the seeding simulations with the scalar seed concentrations and the Lagrangian particle simulations shows an overall consistency. Plumes consistent with the evolving wind are evident in both sets of simulations, and are concentrated in the lowest 0.5 to 1.0-km AGL. The most notable differences are that the main axes of the plumes tend to be somewhat broader in the seeding simulations, as are the entire envelopes of lower concentrations. Both effects are likely due to the numerical diffusion used in the seeding runs, in which gradients in scalar fields are continuously reduced.

The efficiency with which the particles released from the 16 sources are transported over the target area is highly dependent on the meteorological conditions for a given case, as is whether or not the particles are delivered into seedable clouds. To characterize the average conditions over the generator and target areas for each of the six cases, output from the control runs was averaged at the 2-hr archival interval, over a rectangular area 90 km by 120 km. This rectangle just contains the entire 120 km N-S extent of the target area in Figure 3.33, but is shifted westward by 21 km from a location that would contain the entire 90 km E-W extent of the target area. This shift is to avoid conditions (e.g., high amplitude lee waves) along the east slope of the Front Range that might be unrepresentative of meteorological conditions that are relevant for particle transport from the 16 sources to the target area, and also to include conditions west of the target area that are especially relevant for the upstream sources in Groups 1 and 2. Areal average winds over this rectangle were calculated at the lowest terrain-following model level above the surface (about 130-140 m, depending on elevation), while temperature, relative humidity, and total condensate mixing ratio were areally averaged at a constant altitude of 3745-m MSL, which is about 500 m higher than the mean elevation of the model terrain in the target area (3243 m). Thus the average winds include winds from lower elevations where some of the generators are located, as well as winds over higher terrain, all of which are relevant to the transport of particles from source to the target area. The other average variables at 3745-m MSL are intended to indicate conditions that might be favorable for seeding over the target area.

Table 3.9 summarizes the average conditions for each case, as time averaged over a fairly steady extended period (both winds and other variables) representative of the designated wind regime. The averaging period ranges from 14 hr for Feb. 5, 2004 to 24 hr for Nov. 26, 2003. The average wind directions are consistent with the designated wind regime and targeting wind in Table 2.2, with average speeds ranging from 7.5 to 11.8 m/s. The SSW and WSW regimes have average seeding-level temperatures from -6.3 to -2.3°C, while the WNW and NNW regimes are all significantly colder (near -17°C). Average relative humidity ranges from 81 to 89%. These averages generally include higher values near 100% in orographic upslope over higher terrain, as well as lower values in elevated flow over lower elevations and in downslope to the lee of elevated terrain. Because supercooled liquid water is unrealistically low in the model, identification of seedable supercooled cloud is problematic. The mean condensate mixing ratio (generally dominated by aggregates) is used instead, as a measure of active microphysical processes that would likely include seedable orographic cloud. These mean values range from 0.068 to 0.237 g/kg, which like the humidity, are generally much higher over elevated terrain where precipitation is generally enhanced (e.g., Figure 3.1 and Figures 3.4-3.9).

Table 3.9. Average meteorological variables over generator and target area.

Case (yymmdd.00)	Regime (wind flow)	Averaging period (hours from 00 UTC)	Direction /Speed (deg/mps)	Temp (deg C)	RH (%)	Condensate Mixing Ratio (g/kg)
031103.00	SSW	08-24 hrs	231/9.2	-6.3	89	9.126
040102.00	WSW	14-30 hrs	254/11.8	-12.3	86	0.237
031114.00	WSW#2	02-18 hrs	262/9.4	-7.5	87	0.128
031126.00	WNW	08-32 hrs	279/10.1	-16.6	83	0.126
031215.00	NNW	12-28 hrs	310/11.6	-17.7	81	0.145
040205.00	NNW#2	14-28 hrs	336/7.5	-16.7	84	0.068

Notes: Average winds are from lowest model level, about 130-140 m AGL.
Other average variables are at constant altitude of 3745 m MSL.
Mean model elevation in target area is 3243 m MSL.

The particle concentration plumes in Figures 3.34-3.39 show that particles released from sources upstream of the target area for a given wind regime are generally transported over the target area as intuitively intended. The average vertical distribution of those particles is summarized in Table 3.10, where the averaging is done over the same time periods indicated in Table 3.9 and includes only particles within grid cells in the target area and above 50 m AGL. The total number of these particles averages about 23,000 or about 40% of the combined hourly output of the 16 sources. The lowest half-kilometer layer (50 to 500 m AGL) contains an average of 52% of those particles, while the 500-1000 m layer contains another 34% on average. The next two layers on average contain only 10.5% and 2.3%, respectively, of the total number of particles in the target area. Only a minuscule amount gets above 2000 m AGL over the target area, ranging from an average of 0 to 3% of the particles for the six cases. Thus, to the extent that the average conditions at 3745 m MSL in Table 3.9 are indicative of suitable seeding conditions over the target area (with a mean elevation of 3243 m), the great majority of the particles in the lowest two layers (52% and 34% on average, respectively) should be encountering those favorable conditions.

Table 3.11 summarizes the average contribution by each group of generators to the total number of particles over the target area for each case. Again, this time averaging is over the same periods in Table 3.9. The calculation is for the entire 50-2000 m AGL layer, with the great majority of that in the lowest 1000 m. For each case, the four group percentages (top figure in each group block) sum to 100%. Also indicated are time-averaged contributions by each of the four sources in each group (bottom set of figures in each block) to its respective group total, where each set of four percentages also sum to its group total of 100%. The group figures are very consistent with the particular wind regime, with more upstream-situated groups contributing larger relative shares to the total over the target area. For instance, the two southern groups (Groups 1 and 4) deliver their largest contribution to the target area with regimes having a southerly component; the west-northwestern Group 2 makes its largest contribution in the WNW event; and the northern Group 3 makes its largest contribution for the two NNW events. Even though Group 4's largest contribution is in the SSW and WSW events, it is the smallest contributor as an entire group even in those cases. This is largely due to the narrow width of the southeastern finger of the target area along the Rampart Range, such that particles in SSW and WSW flow quickly traverse it.

Table 3.10. Time-average particle statistics over target area – vertical distribution

Case (yymmdd.00)	**Regime (wind flow)**	**# Particles 16 sources (100%)**	**Percent of Particles in Layers**			
			0.05-0.5 km	**0.5-1.0 km**	**1.0-1.5 km**	**1.5-2.0 km**
031103.00	SSW	24,251	54	32	10	3
040102.00	WSW	19,489	52	35	12	2
031114.00	WSW#2	29,078	65	30	4	1
031126.00	WNW	24,727	46	33	13	4
031215.00	NNW	17,897	44	35	16	3
040205.00	NNW#2	20,526	51	39	8	1

Table 3.11. Time-average particle statistics over target area – by group and generator.

Case (yymmdd.00)	**Regime (wind flow)**	**Percent of Total # Particles in Table 3.10 by Groups 1 - 4 (0.5-2.0 km) Percent Contribution by Generator N to each Group Total**			
		Group 1 N = 1 2 3 4	**Group 2 N = 5 6 7 8**	**Group 3 N = 9 10 11 12**	**Group 4 N = 13 14 15 16**
031103.00	SSW	37 32 26 27 14	21 38 40 8 14	26 37 31 10 22	16 27 36 15 22
040102.00	WSW	29 33 30 26 10	31 34 30 17 19	22 52 26 7 15	18 24 15 28 33
031114.00	WSW#2	26 38 33 20 9	29 31 29 20 21	30 43 25 15 17	16 23 26 23 28
031126.00	WNW	17 41 36 22 0	33 25 28 23 24	34 33 26 25 15	15 8 27 25 40
031215.00	NNW	8 21 52 27 0	14 25 24 25 26	70 20 27 30 22	7 0 1 1 98
040205.00	NNW#2	5 22 49 29 0	14 47 13 31 8	80 20 24 14 42	1 1 0 6 93

Careful examinations of the contributions by individual sources versus wind regime are also logical. For instance, source N=4 in Group 1 is furthest down the Arkansas Valley and totally to the lee (south) of the target area in the three WNW and NNW events, and thus contributes no particles to the meager total delivered by the entire group. Even its largest contribution in the SSW and WSW events is small relative to its Group 1 totals, due to the narrow widths of the southern target area fingers along the Mosquito and Rampart Ranges. Similar little or no contributions are seen by the South Park sources N=13, 14 and 15 in Group 4 for the two NNW events. Sources on the northern fringe of the network similarly contribute few particles to the target area in SSW and WSW events (e.g., source N=7 and 8 in Group 2 and N=11 and 12 in Group 3). Source N=12 in Group 3 is located within the target area, but its particles are quickly advected out of the area in S through WNW regimes.

The Lagrangian particle dispersion modeling also provides some insight into the degree to which particles are trapped in low levels. Such trapping can occur in strong inversions in valleys, where the particles remain in relatively still air beneath the targeting winds. Other trapping zones occur in lee-side stagnation points or rotors. Although individual trajectories (not feasible with the 15-min particle position data) are necessary to assess which particles are trapped, low-level concentrations provide evidence of trapping. Recall that the particle concentrations discussed thus far are above 50 m AGL. An examination of particles in the lowest 0 to 50 m AGL shows accumulation regions that may be indicative of trapping. Of course, inversions and lee-side stagnation zones and rotors may be deeper than 50 m, but that layer is sufficiently deep to qualitatively identify such regions. On the other hand, the particle model has some difficulties in calculating trajectories very near the surface, such that some particles apparently get "stuck" and some local high concentrations appear to be artifacts. Such low-level artifacts are why the previous discussion and figures were restricted to above 50 m AGL.

Samples of 0-50 m concentration fields are illustrated for the Jan. 2, 2004 WSW event, with the same contour interval of 50 particles per grid cell used in Figures 3.34-3.39. Figure 3.40 is at 18 hr, early in the extended steady phase and during the daytime, while Figure 3.41 is at 30 hr, at the end of the steady WSW phase and near midnight. During the daytime, low level concentrations around most of the sources appear quite similar, with most of the particles getting above 50 m and advecting downstream with the targeting wind (compare with 50-2000 m concentrations at 20 hr in Figure 3.35). The most notable exception is the northern source N=11 in Group 3, which has a more extensive and higher-valued low level concentration than the other sources. Source N=9, also in Group 3 in the upper Blue Valley, has a smaller but very high-valued maximum. Both of these sources are in lee subsidence zones in the WSW flow, such that many particles are either quickly stuck at the surface or remain relatively stationary in stagnation zones. Generators situated in such recurrent stagnation zones may not be very effective in delivering seeding material in the intended downwind direction. Note also the local maximum originating from Group 2 (green) far downstream of those sources (N=5-8), between the two Group 3 sources N=10 and 11 on the lee side of the Gore Range. A similar local maximum originating from Group 3 (yellow) is seen well downstream of those sources (N=9-12) along the east slope of the Front Range. Such a maximum may be partly artificial due to near-surface trajectory modeling difficulties, but are probably also indicative of high-amplitude lee waves, rotors, and low-level stagnation zones.

Near midnight (Figure 3.41) there is evidence of low-level inversions being established over most of the sources, with much higher concentrations than seen during the daytime in Figure 3.40. The Group 1 sources N=2, 3 and 4 and Group 2 source N=5 are the exceptions, with their lower valued maximum about the same as seen during the daytime. The same local daytime maxima that are remote from their sources are seen in this nocturnal phase, with an additional large remote maximum originating from Group 4 (red) seen to the lee of the Rampart Range.

An examination of 6-hr low-level concentration fields was done for all six cases, concentrating on the extended periods of relatively steady conditions noted in Table 3.9. In general, nocturnal trapping was noticeable for all Groups, and usually more prevalent during the second nocturnal period (recall that the model ran from 0000 UTC or 1700 MST, or the beginning of the first nocturnal period, through 36 hr to 1200 UTC or 0500 MST, near the end of the second nocturnal period). This more extensive trapping the second night is likely due to stronger inversions being established in colder, drier, post-frontal air masses moving in after the main seeding event. As in Figure 3.41, Group 1 sources N=2, 3 and 4 appeared to be least susceptible to trapping, especially in the SSW and WSW events. Sources N=11, followed by N=9 and 12, all in the northern Group 3, appeared to be the most frequent local trapping zones, primarily in SSW through WNW events, and even during the daytime. These are all to the lee of either the Gore or Williams Fork Ranges and are likely zones of high amplitude lee waves, rotors and stagnation zones. Trapping was much reduced at these sites in the NNW events, when they are not on the lee side of mountain ranges in the NNW flow.

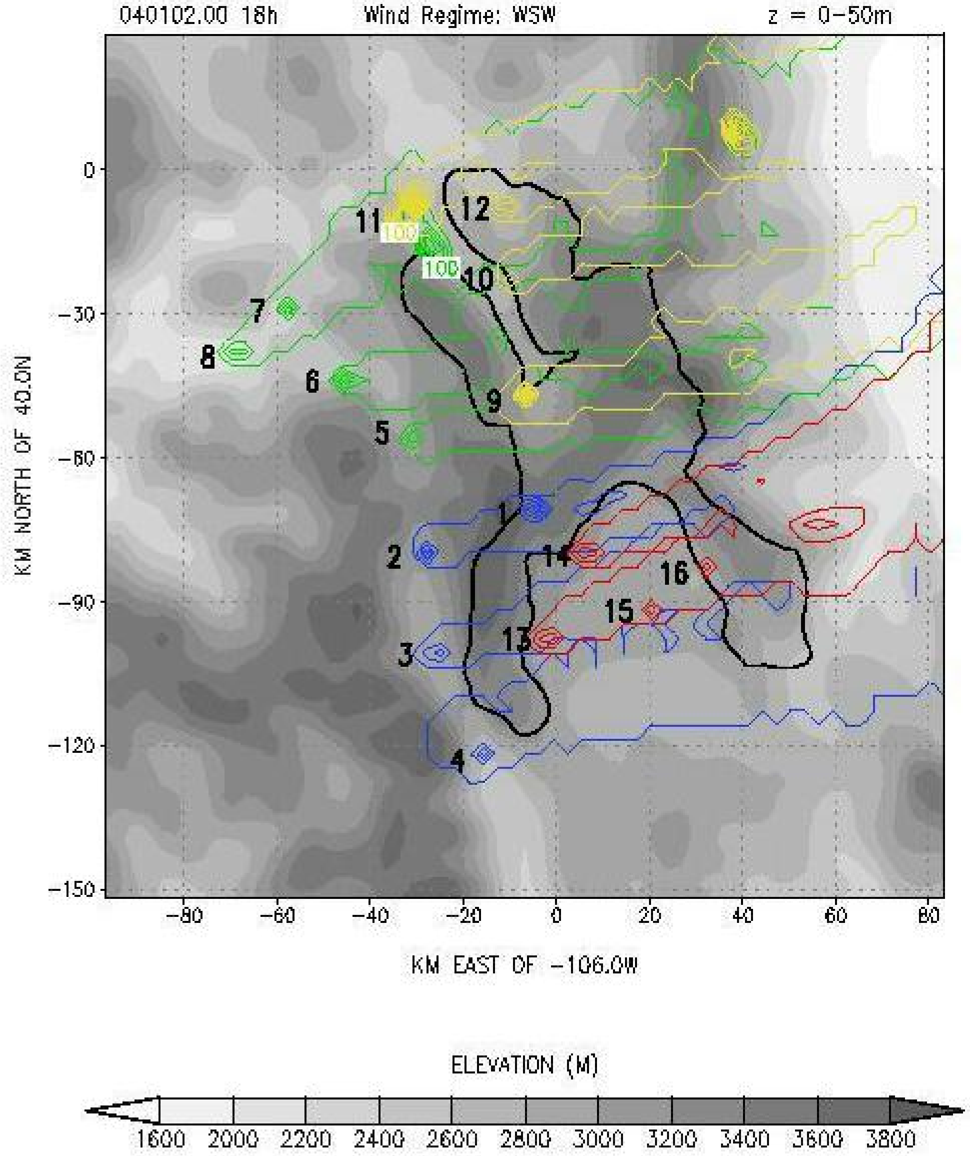


Figure 3.40. Particle concentration fields (0-50 m AGL) for the Jan. 2, 2004 WSW regime at hour 18 (1100 MST - daytime extended steady state phase).

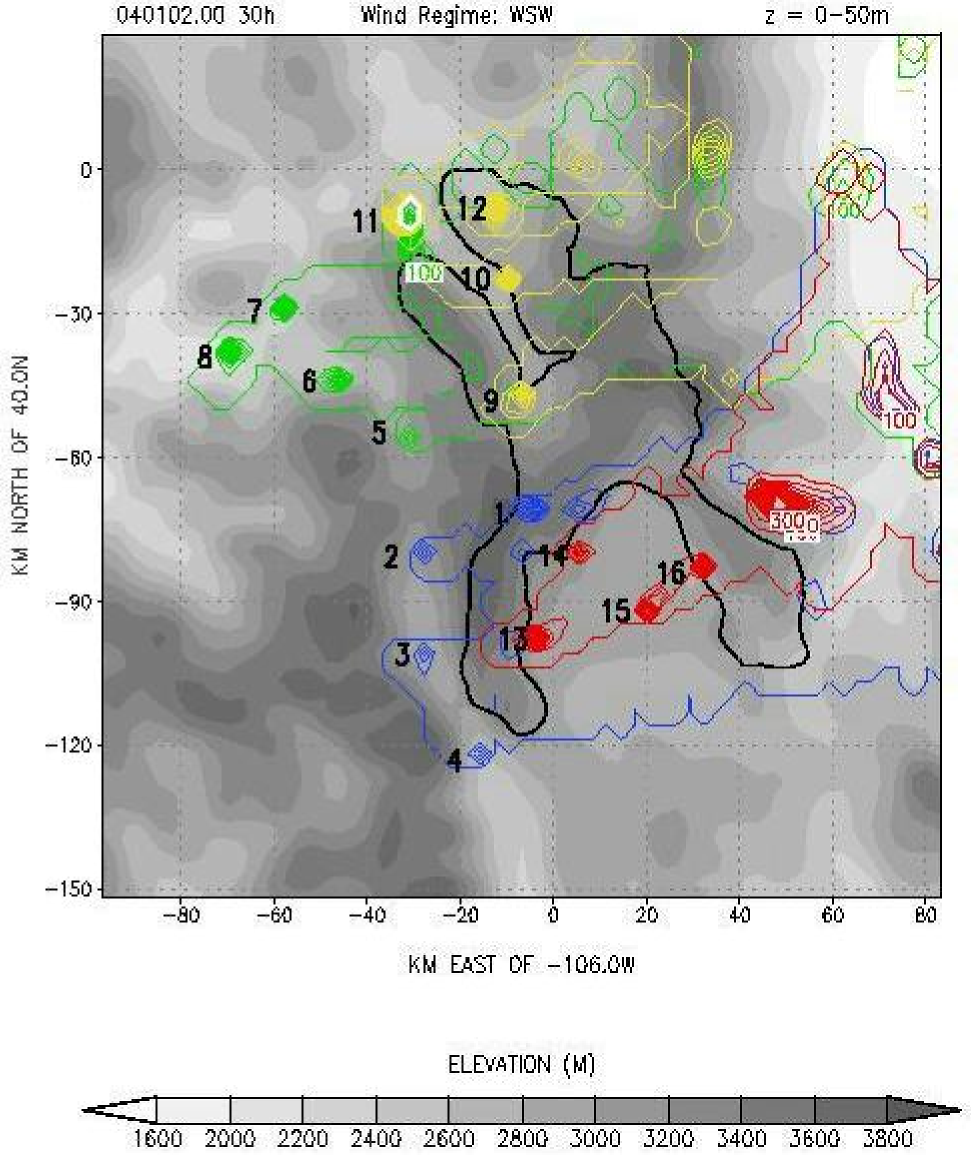


Figure 3.41. Particle concentration fields (0-50 m AGL) for the Jan. 2, 2004 WSW regime at hour 30 (2300 MST - near the end of steady state phase).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions from the Colorado WDMP Research Project

The Colorado WDMP research project involved a physical evaluation of the Denver Water (DW) operational winter orographic seeding program in the central Colorado Rockies for the winter season 2003-2004 using the RAMS mesoscale model. The project was piggy-backed onto the DW operational program contracted by Western Water Consultants, LLC. The target area was the Blue, Upper Blue, Snake, Williams Fork, and Upper South Platte River drainage basins (see Figure 2.1). Using a finest grid spacing of 3 km, RAMS was run first in real-time to provide operational support to the DW cloud seeding program. RAMS was subsequently rerun for the period of operations with a number of improvements derived from assessments of the real-time runs, and then rerun with simulated seeding generators releasing seeding material (AgI) at rates, time periods, and locations consistent with the operational program.

As a mesoscale model, RAMS is unique in its ability to explicitly represent the activation of cloud nucleating aerosols (CCN and IN) including seeded IN, to simulate the transport and dispersion of seeding material, the explicit nucleation and vapor deposition, riming, and aggregation growth of ice particles, and amounts and types of precipitation. Moreover, it was able to do so for an entire operational cloud seeding program. We believe that this project establishes a “model” of a methodology for physical and statistical evaluation of future seeding projects. However, it must be recognized that this was a first prototype model and as such, things did not work out entirely according to our expectations.

The major results of this study are as follows:

- WWC (Larry Hjermstad) found that after the model fixes had been implemented in mid-February 2004 and the RAMS real-time forecast 0000 UTC cycle was run on the new PC cluster, the forecast output that was posted on the Web site was very useful. The low-level warm temperature problem had been greatly reduced and the model provided timely input for operational cloud seeding decision making. There were numerous forecast products and parameters to evaluate. In addition to the 2-hr forecast presentations, the animated forecast loops provided a quick visual picture of changes over time.
- Larry Hjermstad did point out the forecast model exhibited a warm temperature bias at 700 mb which reduced its effectiveness as a decision tool for determining if seeding operations should proceed. Causes of the warm bias were determined and fixes were made in mid-February 2004. The entire winter season was rerun to provide a better estimate of natural and seeded precipitation. However, the model fixes did not entirely eliminate the low-level warm bias. After the final fixes were made to the model, two case studies were run (see Subsection 3.6). Although this was

a limited sample, these case studies showed the at the 700 mb level (about 10,000 ft) the warm temperature bias could be as much as + 2°C. This probably isn't enough to have a "major" impact on seedability.

- Working with Larry Hjermstad, the best 30 cloud-seeding days were selected for use in post-season research evaluations. When model simulated precipitation was compared to measured 24-hr precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88. The highest bias areas included the Target Area. The lowest bias areas were in more upwind areas in northwesterly and southwesterly events. Possible sources of those biases are discussed in Subsection 3.2 and are currently still under investigation.
- The model control simulations produced a reasonable qualitative pattern of total precipitation and its topographic dependence for the 30 selected days. The 30-day simulated precipitation total showed only light precipitation over the entire SE leg and south half of the SW leg of the target area (see Figure 3.1). Thus the model suggests little orographic precipitation potential and perhaps little cloud seeding potential over the two south legs of the target area.
- The model forecast precipitation data were evaluated against SNOTEL data using MRBP statistical analysis procedures. The results from the evaluation show that the model is describing the non-seeded and seeded precipitation equally well. While the signal of the fits is strong (all P-values about 1.0E-6 or less), the agreement measures are not outstanding (all fall between 0.18 and 0.26).
- Comparison of model-predicted precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals (difference of -1.0 mm) or the 30-days selected for model precipitation evaluation seed and control average totals (difference of -0.2 mm).
- Langrangian trajectory analyses of six selected days of the subset of 30 days selected for precipitation evaluation revealed that particles are generally being transported to the target area by the targeting wind as intended. On average, 54% of those particles are 50-500 m AGL, with another 34% in the layer 500-1000 m AGL, which are levels suitable for AgI seeding.
- The Lagrangian analyses confirm that generators should not be used when the targeting wind would not carry their plumes over the target area. Low level trapping of particles can become moderate in nocturnal inversions, but significant numbers of particles escape the inversions and are transported by the targeting wind as intended. It appears that generators located on the lee side of mountain ranges may be in stagnation zones or rotors associated with high amplitude mountain waves, and their particles are also subject to moderate local trapping.

The very small difference between seed and control precipitation predicted by the model was disappointing and not expected at the onset of this project. Possible causes of such low seedability include:

- The model predicted seedability could be real; however, because of the model over precipitation bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- The background CCN and IN concentrations are unknown but instead are determined by our selected background concentrations. Too low a background CCN concentration would make clouds more efficient in natural precipitation formation thereby lowering seedability. Too high background IN concentrations would likely lead to lower seedability.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby lowering seedability
- The evaluated over-prediction bias in precipitation may lead to reduced opportunities for precipitation enhancement in the model.
- Banded patterns of seed – no-seed differences on daily totals suggest a possible dynamic response to seeding. This pattern of differences results in much of the target area being in regions of reduced precipitation.
- The low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent. However, this effect has overall a small impact on seedability.
- The simulated transport and diffusion of seeding material from the generator sites is getting into the clouds too far downwind of the generator sites. However, the particle modeling suggests that seeding material is delivered to the target area at levels suitable for seeding, which argues against the notion that seeding material is not getting into the intended seeding zones.

4.2 Recommendations for Future Research and Operational Projects

Because this was only a one-year contract and the research funding was limited, there are many aspects of this research that remain to be done. The DW 2003-2004 operational cloud-seeding program began on November 1, 2003, and the cloud seeding activities for much or the target area ended on February 10, 2004 (see Subsections 2.2 and 3.1). CSU's purchase of an additional PC cluster that was needed to produce timely model forecast runs was delayed due to the requirement to wait for the signing of an Interagency Agreement between CSU and the CWCB. Consequently, the initial model runs were made on an old PC cluster that was about 3-times slower than desired. CSU was able to switch to a faster PC cluster on January 10, 2004, but the new PC cluster was not operational until mid-February 2004. Switching to the faster PC cluster allowed WWC (Larry Hjermstad) to utilize the RAMS forecast output in near real-time. WWC's attempt to use the RAMS real-time forecasts led to the discovery of several model problems (reference Subsection 2.7 Task 4). The final model fixes for the project were in place starting with the February 14, 2004 real-time run.

Solving and implementing the model fixes required unexpected time/cost to the project, which limited the number of sensitivity tests that could be run.

Recommendations for future combined research and operational projects:

- Determine the cause of the model over-prediction bias in precipitation.
- Determine the magnitude and cause of the low-level warm temperature bias.
- Explore the various hypotheses that have been put forward to explain the very small differences between seed and no-seed precipitation amounts.
- Explore the reason for almost non-existent SLW in the 2-hr vertically integrated maps over the target area.
- Rerun all or at least the 30 selected days with higher grid resolution (e.g. 1 km) to determine if increased resolution reduced the precipitation bias and/or the seed, no-seed differences.
- Perform more comparisons of 24-hr model simulated precipitation forecasts with SNOTEL observations to further examine the accuracy of the model's precipitation distribution patterns.
- Utilize the model's quantitative precipitation patterns over the target area to improve the design of the cloud seeding generator network.
- Perform additional Lagrangian model simulation transport and dispersion studies to improve understanding which cloud seeding generators to utilize under various wind flow regimes.
- Install rime ice detectors at the top of nearby ski areas to provide some quantitative information of the presence of SLW. (Perhaps some of the cooperating ski areas would be willing to purchase, install and maintain these sensors.)
- Install a vertically-pointing radiometer near the summit of several mountain ranges for SLW detection.

In support of future operational cloud seeding projects in which a model is used as part of the evaluation technique, it is urged that background CCN and IN concentrations be measured. Preferably this would be airborne but in lieu of that longer term ground-based measurements, particularly from higher-terrain sites would be desirable. Another item that would be very useful on such a research project would be the use of a scanning cloud radar for identifying regions of liquid water in the clouds and to follow precipitation morphology. Such a cloud radar system installed just upwind of the target area barrier for even a month or two would provide valuable data for comparison with mesoscale model forecast output. In addition the combination of model predictions and new observations such as cloud radar and radiometers could be used in a very sophisticated method of evaluation of an operational seeding project.

REFERENCES

American Meteorological Society (AMS), 1998a: Policy Statement, Planned and Inadvertent Weather Modification (adopted by the AMS Council 2 October 1998). *Bull. Amer. Meteor. Soc.,* 79, 2271-72.

American Meteorological Society (AMS), 1998b: Scientific Background for the AMS Policy Statement on Planned and Inadvertent Weather Modification, 1998. *Bull. Amer. Meteor. Soc.,* 79, 2273-2278.

Cotton, W.R., G. Thompson, and P.W. Mielke, Jr., 1994: Real-time mesoscale prediction on workstations. *Bull. Amer. Met. Soc.,* 75, 349-362.

Cotton, W.R., R.A. Pielke, Sr., R.L. Walko, G.E. Liston, C.J. Tremback, H. Jiang, R.L. McAnelly, J.Y. Harrington, M.E. Nicholls, G.G. Carrio, J.P. McFadden, 2003: RAMS 2001: Current status and future directions. *Meteor. Atmos. Physics*, 82, 5-29.

Doesken, N.J., T.B. McKee, and B. Richter, 1984: Analysis of Colorado average annual precipitation for the 1951-1970 period. Climo Rpt 84-4, Dept. of Atmos.Sci., CSU, Fort Collins, CO, 53 pp.

Gaudet, B., and W.R.Cotton, 1998: Statistical characteristics of a real-time forecasting model. *Wea. Forecasting*, 13, 966-982.

List, Roland, 2005: The Unfortunate Academy Report on Weather Modification. *Preprints, 16th Conference on Planned and Inadvertent Weather Modification,* Amer. Meteor. Soc., San Diego, CA, paper P1.11.

Mielke, P.W., 1984: Meteorological applications of permutation techniques based on distance functions. *Handbook of Statistics*, Vol. 4, P.R. Krishnaiah and P.K. Sen, Eds., Elsevier, 813-830.

Mielke, P.W., 1991: The application of multivariate permutation methods based on distance functions in the earth sciences. Earth-Sci. Rev., 31, 55-71.

Mielke, P.W., 2001: Dr. Mielke's book - PERMUTATION METHODS: A DISTANCE FUNCTION APPROACH*, Springer-Verlag, 352 pages.*

National Research Council, Committee on the Status of and Future Directions in U.S. Weather Modification Research and Operations, 2003: Critical Issues in Weather Modification Research. *The National Academies Press*

Uliasz M., R.A. Stocker, and R.A. Pielke, 1996: Regional modeling of air pollution transport in the southwestern United States. Chapter 5 in *Environmental Modeling*, Volume III, Zannetti P, Ed., Computational Mechanics Publications, 145-181.

Weather Modification Association (WMA), 2005: WMA Capability Statement on Weather Modification (adopted by the WMA Council April 2005).

Wetzel, M., M. Meyers, R. Borys, R. McAnelly, W. Cotton, A. Rossi, P. Frisbie, D. Nadler, D. Lowenthal, S. Cohn, and W. Brown, 2004: Mesoscale snowfall prediction and verification in mountainous terrain. *Weather and Forecasting,* **19**, 806-828.

World Meteorological Organization (WMO), 2001: WMO Statement on the Art of Weather Modification. Executive Council Meeting LIII, Geneva, June, pp 7.

APPENDIX 1

WWC Cloud-Seeding Generator Sites for 2003-2004 Denver Water Program

ID	Latitude	Longitude	Elevation (ft)	Program	Site Name
V1	39.90117	-106.59550	7088	V/BC/DW	McPhee Gulch
V2	39.95017	-106.70783	7433	V/BC/DW	Conger Mesa
V6	39.78400	-106.68850	8194	V/BC/DW	Wolcott Divide
V8	39.73383	-106.68083	7234	V/BC/DW	4 Eagle Ranch
V10	39.70200	-106.67983	6970	V/BC/DW	Wolcott
V15	39.60266	-106.54300	9540	V/BC/DW	Beaver Creek
D1	39.11967	-106.03333	9595	DW	Round Hill
D2	39.08383	-105.89467	9094	DW	Fourmile Creek
D3	39.02150	-105.79684	8861	DW	Hartsel
D4	39.24434	-105.63934	8906	DW	Eagle Rock Ranch
D5	39.17250	-105.77717	9579	DW	Ruby Gulch
D6	39.17317	-105.95483	9543	DW	Middle Fork Ranch
D7	39.09000	-106.30666	9667	DW/UA	Twin Lakes
D8	39.25050	-106.05450	10295	DW	Pennsylvania Creek
D9	39.27667	-105.93350	9583	DW	Red Hill Pass
D10	39.26033	-105.77400	9433	DW	Indian Gulch
D11	39.26583	-105.72250	9515	DW	Stage Stop
D12	39.36817	-105.74983	9817	DW	Jefferson
D13	39.19333	-106.35083	9414	DW/UA	Crystal Lakes
D14	39.27400	-106.33500	9898	DW/UA	Leadville
D17	39.50733	-106.36633	8681	DW/UA	Redcliff
D19	40.14400	-106.46500	7725	DW	Pass Creek
D21	40.09367	-106.20433	7829	DW	Parshall
D26	40.06883	-106.08250	7932	DW	Hot Sulfur Springs
D27	40.00433	-106.18217	7949	DW	Williams Fork E
D28	40.00433	-106.22884	7820	DW	Williams Fork W
D29	40.01617	-106.35184	7574	DW	Rusty Spur
D30	39.90517	-106.40183	9011	DW	Spring Creek
D31	39.92867	-106.33533	7726	DW	Haystack Ranch
D32	39.85383	-106.29850	8508	DW	Cataract Creek
D33	39.57150	-105.88184	10779	DW	Saints John
D34	39.83800	-106.23267	7988	DW	Butler Gulch
D35	39.92883	-106.13667	8440	DW	Lost Creek
D36	39.79583	-106.12783	8546	DW	Big Gulch
D37	39.66450	-106.08033	8622	DW	Hamilton Creek
D38	39.56800	-106.08667	9099	DW	Frisco
D39	39.54467	-106.04750	9340	DW	Gold Hill
D40	39.44533	-106.04450	10123	DW	Breckenridge
D41	39.35500	-106.06500	11094	DW	Hoosier Pass

V = Vail & BC = Beaver Creek   DW = Denver Water   UA = Upper Arkansas

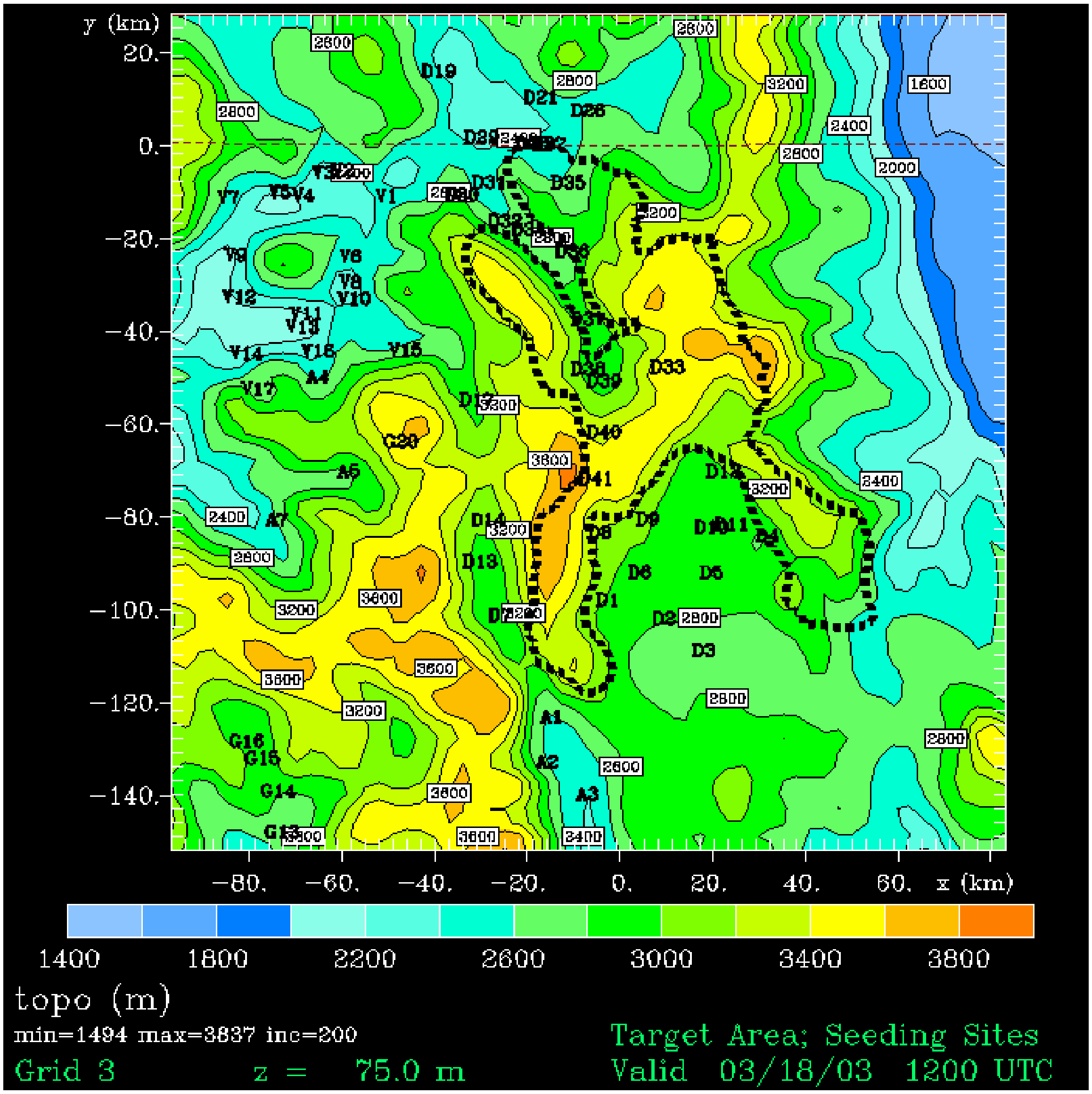


Figure A1.1. Locations of DW Program cloud-seeding generator sites.

APPENDIX 2

Natural Resources Conservation Service SNOTEL Sites in Colorado

NO.	SITE NAME	LATITUDE	LONGITUDE	ELEV	SITE ID	GPS ID
1	Apishapa	37.330620	-105.067490	10000	05M07S	APISH
*2	Arapaho Ridge	40.350983	-106.381416	10960	06J08S	
*3	Arrow	39.915497	-105.760834	9680	05K06S	ARROW
*4	Bear Lake	40.311176	-105.644836	9500	05J39S	BEARL
5	Beartown	37.714092	-107.512123	11600	07M32S	BERTN
*6	Beaver Creek Village	39.599167	-106.511414	8500	06K45S	
*7	Berthoud Summit	39.803917	-105.777893	11300	05K14S	BRTSM
*8	Bison Lake	39.764866	-107.356812	10880	07K12S	BISON
*9	Brumley	39.087662	-106.541702	10600	06K40S	BRUML
*10	Buckskin Joe	39.303501	-106.113068	11150	06K16S	BUKSKN
*11	Buffalo Park	40.228611	-106.595276	9240	06J18S	BUPARK
*12	Burro Mountain	39.875050	-107.598534	9400	07K02S	BURRO
*13	Butte	38.894325	-106.953003	10160	06L11S	BUTTE
14	Cascade	37.650963	-107.805061	8880	07M05S	CASCD
15	Cascade #2	37.658001	-107.802681	8920	07M35S	CASC2
*16	Columbine	40.394798	-106.604080	9400	06J03S	COLUL
17	Columbine Pass	38.417946	-108.382492	9400	08L02S	COLPA
18	Columbus Basin	37.441471	-108.024445	10785	08M10S	CBSBN
*19	Copeland Lake	40.207775	-105.568611	8600	05J18S	
*20	Copper Mountain	39.489540	-106.170952	10500	06K24S	COPPR
*21	Crosho	40.167454	-107.057503	9100	07J04S	CROSH
22	Culebra #2	37.209450	-105.199585	10500	05M03S	CULEB
23	Cumbres Trestle	37.018776	-106.451790	10040	06M22S	CUMBR
*24	Deadman Hill	40.805714	-105.769928	10220	05J06S	DEADM
*25	Dry Lake	40.533974	-106.781296	8400	06J01S	DRYLA
*26	Echo Lake	39.656265	-105.593452	10600	05K27S	ECHOLK
27	El Diente Peak	37.786167	-108.021545	10000	08M06S	ELDIE
*28	Elk River	40.847813	-106.968704	8700	06J15S	ELKRI
*29	Fremont Pass	39.379913	-106.196808	11400	06K08S	FREMT
*30	Grizzly Peak	39.646313	-105.869728	11100	05K09S	GRZPK
*31	Hoosier Pass	39.361267	-106.059784	11400	06K01S	HSRPS
32	Idarado	37.933903	-107.675522	9800	07M27S	IDARA
*33	Independence Pass	39.075386	-106.611694	10600	06K04S	INDPA
*34	Ivanhoe	39.292023	-106.549232	10400	06K10S	IVANH
*35	Jackwhacker Gulch	39.566666	-105.800003	10960	05K26S	
*36	Joe Wright	40.532146	-105.887001	10120	05J37S	JOEWR
**37	Jones Pass	39.764500	-105.906235	10400	05K21S	JONES
*38	Kiln	39.317238	-106.614525	9600	06K30S	KILN
*39	Lake Eldora	39.936783	-105.589561	9700	05J41S	ELDOR
*40	Lake Irene	40.414326	-105.819801	10700	05J10S	LKIRE
41	Lily Pond	37.379288	-106.548347	11000	06M23S	LILY
42	Lizard Head Pass	37.799255	-107.924263	10200	07M29S	LIZAR
43	Lone Cone	37.891827	-108.195442	9600	08M07S	LONEC
*44	Lost Dog	40.815884	-106.748352	9320	06J38S	LSTDOG
*45	Loveland Basin	39.674332	-105.901337	11400	05K05S	LVLAND
*46	Lynx Pass	40.078056	-106.670280	8880	06J06S	LYNX
47	Mancos	37.430870	-108.169540	10000	08M02S	MANCO
*48	Mc Clure Pass	39.128967	-107.288063	9500	07K09S	MCCLU

*49	Mc Coy Park	39.604683	-106.541283	9480	06K44S	
50	Medano Pass	37.851635	-105.436134	9649	05M16S	
*51	Mesa Lakes	39.058308	-108.058350	10000	08K04S	MESAL
*52	Michigan Creek	39.433334	-105.916664	10600	05K28S	
53	Middle Creek	37.619785	-107.034821	11250	07M21S	MIDCR
*54	Middle Fork Camp	39.795601	-106.027298	9000	06k12s	MFORKC
55	Mineral Creek	37.847473	-107.726570	10040	07M14S	MINCR
56	Molas Lake	37.749325	-107.688652	10500	07M12S	MOLAS
*57	Nast Lake	39.297222	-106.606941	8700	06K06S	NASTLK
*58	Never Summer	40.404049	-105.955833	10280	06J27S	
*59	Niwot	40.035233	-105.544258	11300	05J42S	NIWOT
*60	North Lost Trail	39.078133	-107.143890	9200	07K01S	NLOST
*61	Overland Reservoir	39.090553	-107.634720	9840	07K14S	
*62	Park Cone	38.819954	-106.589745	9600	06L02S	PARKC
*63	Park Reservoir	39.046440	-107.874138	9960	07K06S	PARKR
*64	Phantom Valley	40.399368	-105.847565	9030	05J04S	PHANT
*65	Porphyry Creek	38.488842	-106.339653	10760	06L03S	PORPY
*66	Rabbit Ears	40.367825	-106.740379	9400	06J09S	RABBI
*67	Rawah	40.707500	-106.007599	9020	06J20S	
68	Red Mountain Pass	37.891804	-107.713417	11200	07M33S	REDMO
*69	Ripple Creek	40.108124	-107.294113	10340	07J05S	RIPPL
*70	Roach	40.875023	-106.046028	9700	06J12S	ROACH
*71	Rough And Tumble	39.033333	-106.083336	10360	06K43S	
*72	Schofield Pass	39.015221	-107.048767	10700	07K11S	SCHPA
73	Scotch Creek	37.645554	-108.007858	9100	08M08S	SCOTY
74	Slumgullion	37.991516	-107.204140	11440	07M30S	SLUMG
75	South Colony	37.968105	-105.537865	10800	05M13S	SCOLO
76	Spud Mountain	37.698662	-107.777145	10660	07M11S	SPUDM
*77	Stillwater Creek	40.225433	-105.919769	8720	05J12S	STILL
78	Stump Lakes	37.476212	-107.632950	11200	07M34S	STUMP
*79	Summit Ranch	39.717957	-106.158012	9400	06K14S	SUMRA
*80	Tower	40.537426	-106.676796	10500	06J29S	TOWER
*81	Trapper Lake	39.998840	-107.236198	9700	07K13S	TRAPP
82	Trinchera	37.353279	-105.232330	10860	05M08S	TRINC
*83	University Camp	40.032784	-105.576149	10300	05J08S	UNICA
84	Upper Rio Grande	37.721943	-107.260147	9400	07M16S	URIOG
85	Upper San Juan	37.485760	-106.835350	10200	06M03S	SJUAN
86	Ute Creek	37.614967	-105.373268	10650	05M17S	UTECRK
*87	Vail Mountain	39.616764	-106.380058	10300	06K39S	VAILM
88	Vallecito	37.485096	-107.506798	10880	07M31S	VALLE
89	Whiskey Creek	37.214108	-105.122444	10220	05M14S	WHISK
**90	Wild Basin	40.200001	-105.599998	9600	05J05S	
*91	Willow Creek Pass	40.347034	-106.094330	9540	06J05S	WLLCK
*92	Willow Park	40.432541	-105.733368	10700	05J40S	WILLP
93	Wolf Creek Summit	37.479214	-106.801704	11000	06M17S	WOLFC
*94	Zirkel	40.794884	-106.595352	9340	06J19S	

*SNOTEL Site located within RAMS Grid 3 (63 sites)

**SNOTEL Site with obviously bad data – not used in CSU studies

Yellow-hilite Sites used in MRBP statistical studies (30 sites)

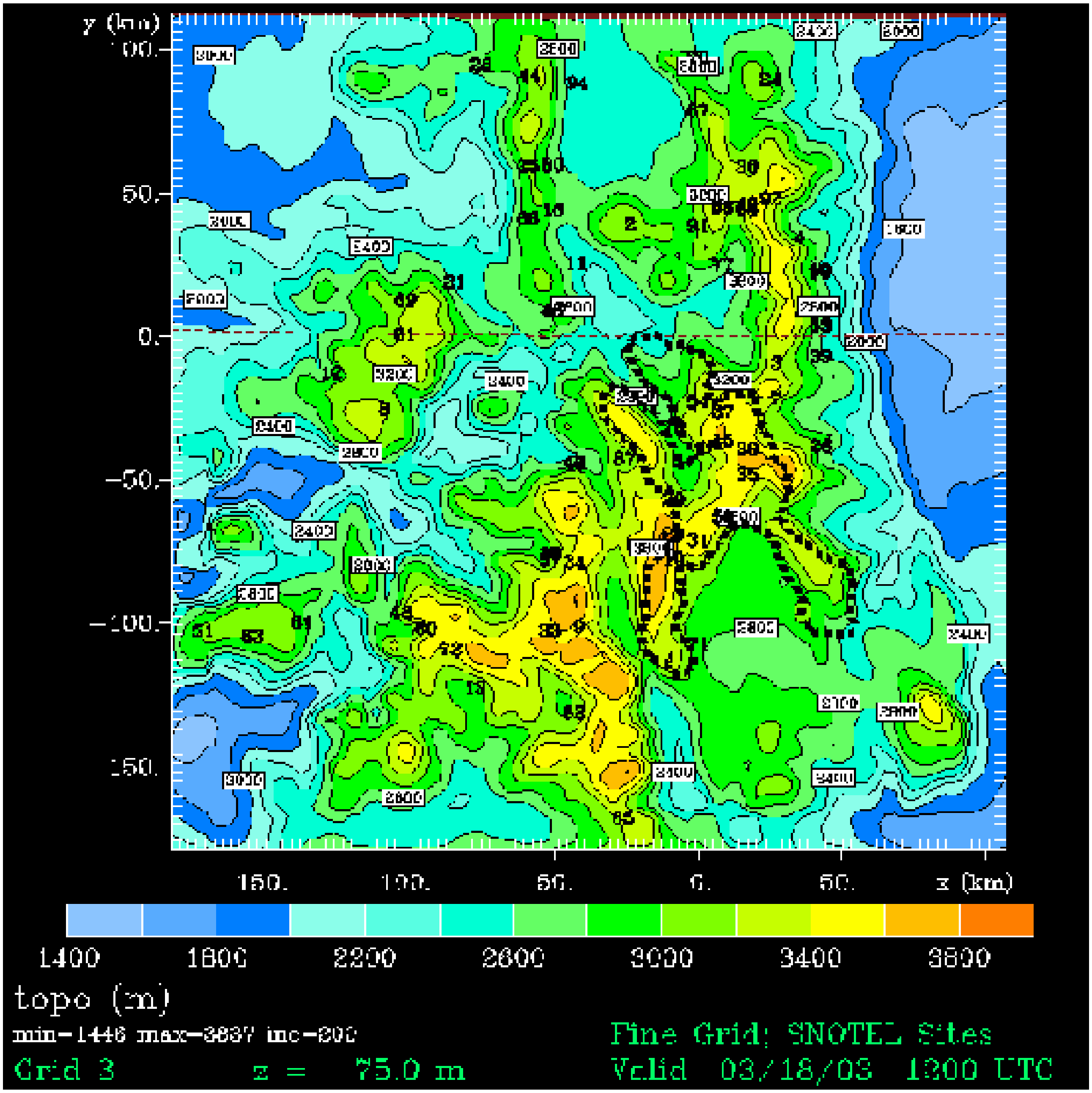


Figure A2.1. Locations of SNOTEL sites in RAMS Grid 3 – dashed line is the boundary for the Denver Water 2003-2004 Program target area.

APPENDIX 3

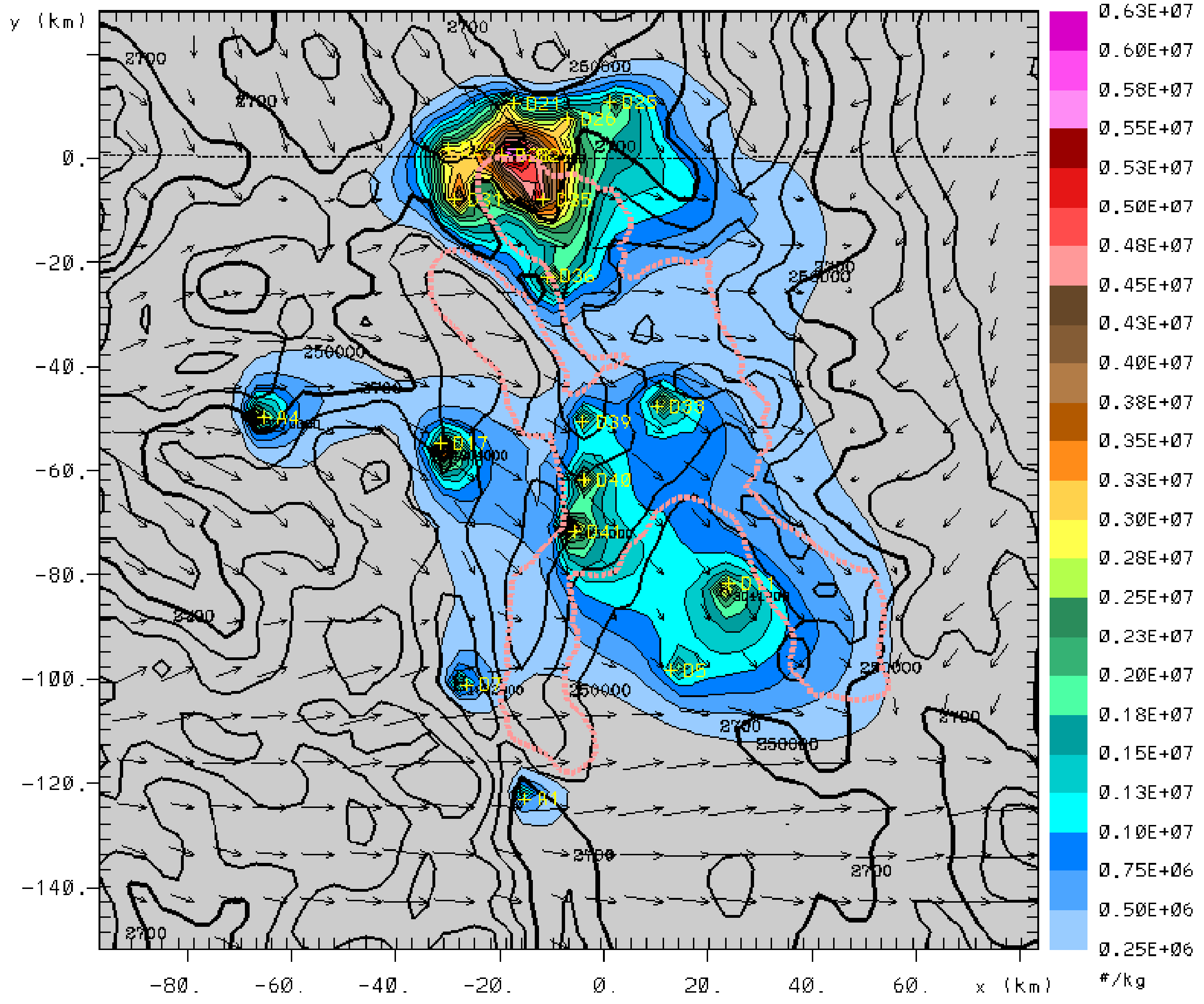
Seeding Test Case – February 4, 2003
by Ray McAnelly and Gustavo Carrió

The test case simulations were initialized at 0000 UTC on February 4, 2003 and were run for 36 hours to 12 UTC on February 5. From the seeding run, Figure A3.1 shows the available seeded IFN concentration at the lowest model level at 24 hours into the run, well after all 19 of the generators used on this day had been activated. Only a portion of the 3-km fine grid is shown, zoomed into the target area. All 19 of the generator locations are marked, using the identifiers adopted for the 2003-2004 season. Generator D25 was deactivated for the 2003-2004 season, and D5 was moved a few kilometers northeast from its 2002-2003 position shown in Figure A3.1. The other WWC generators were at near-identical locations for the two seasons. The local maxima indicate the sources of seeded IFN in the 3-km x 3-km grid cells that contain the generators. Much diluted concentrations are seen in the merged plumes that advect downwind toward the east and southeast.

Figure A3.2 shows the vertically integrated concentration of activated seeded IFN, or pristine ice crystals that are nucleated on seeded IFN. The entire 3-km grid is shown. Two primary plumes are evident, one originating from the northern cluster of generators seen in Figure A3.1 and the other from the southern cluster. A west-to-east vertical cross section in Figure A3.3 is through the southern maximum seen in Figure A3.2 and also through generator D11's location in Figure A3.1. The black contours show the available seeded IFN concentration, with a surface maximum at the D11 generator location and extending upward and downwind in diffuse concentrations to about 3 km AGL. The color-contoured field is the activated seeded IFN (ice crystal) concentration, with a maximum activation region about 1.5 km over the crest of the Rampart Range in NW Colorado. A similar plot of total pristine ice concentration along the same cross section (not shown) indicates the elevated band extending all the way westward across the domain, with the upstream portion due to nucleated background IFN. This main activation zone is between -20 and -25°C for both background and seeded IFN.

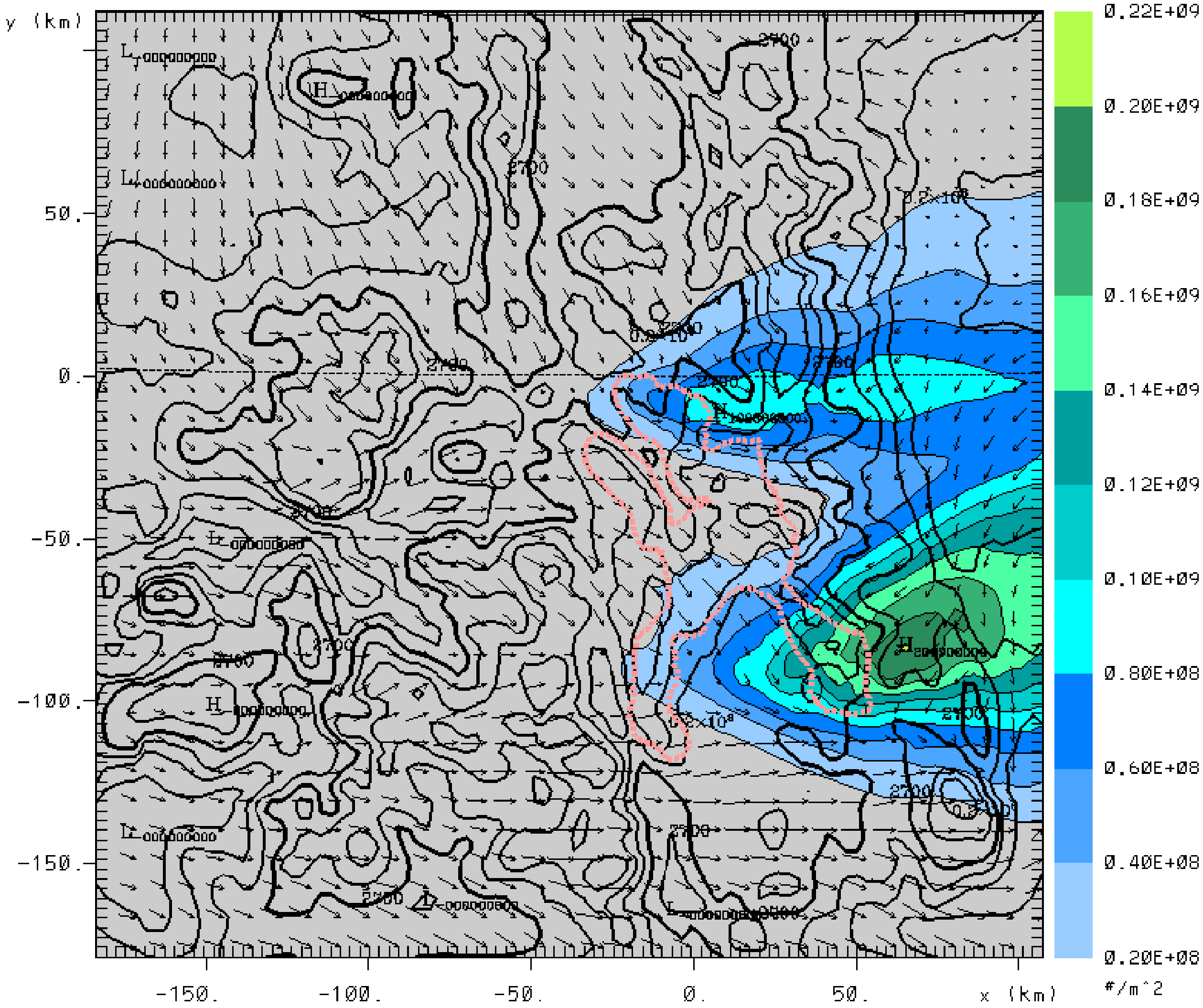
In the control run for this test case, the model setup is identical to the seeded simulation except that there is no seeded IFN. Simulated 24-hr precipitation on the 3-km grid from 0800 UTC on February 4 to 0800 UTC on February 5 is shown in Figure A3.4. This period was chosen to coincide with 24-hr precipitation and snow water equivalent reporting times for the SNOTEL network. The first 8 hours of the seeding simulation allows ample time for any seeding material released early in the run to be transported over the target area and become microphysically active well before the 24-hr precipitation period. The control run shows precipitation maxima of about 15 mm along the western and northern ridges in the target area, with larger maxima to the west and particularly along the eastern flank of the northern Front Range. Very little precipitation is simulated at lower elevations. A cursory comparison with SNOTEL and CoCoRaHS observations suggests that the simulated precipitation is fairly accurate over the target area and much of the domain, but may be over-predicted by a factor of 2 or 3 along the Front Range maximum.

The corresponding 24-hr precipitation for the seeding simulation is not shown because it is almost identical to the control run. This is evident in Figure A3.5, which shows the seeded - control 24-hr precipitation difference field. Very small positive and negative differences (<0.05 mm) are organized into bands about 30-50 km wide, and aligned west-to-east along the prevailing westerly flow direction. This very small response to seeding is even less than the small response generally seen in other sensitivity runs (Task 4). The domain-wide banded patterns are typical and indicate an unexpected seeding response, albeit very small, extending well away and even upstream from the target area.



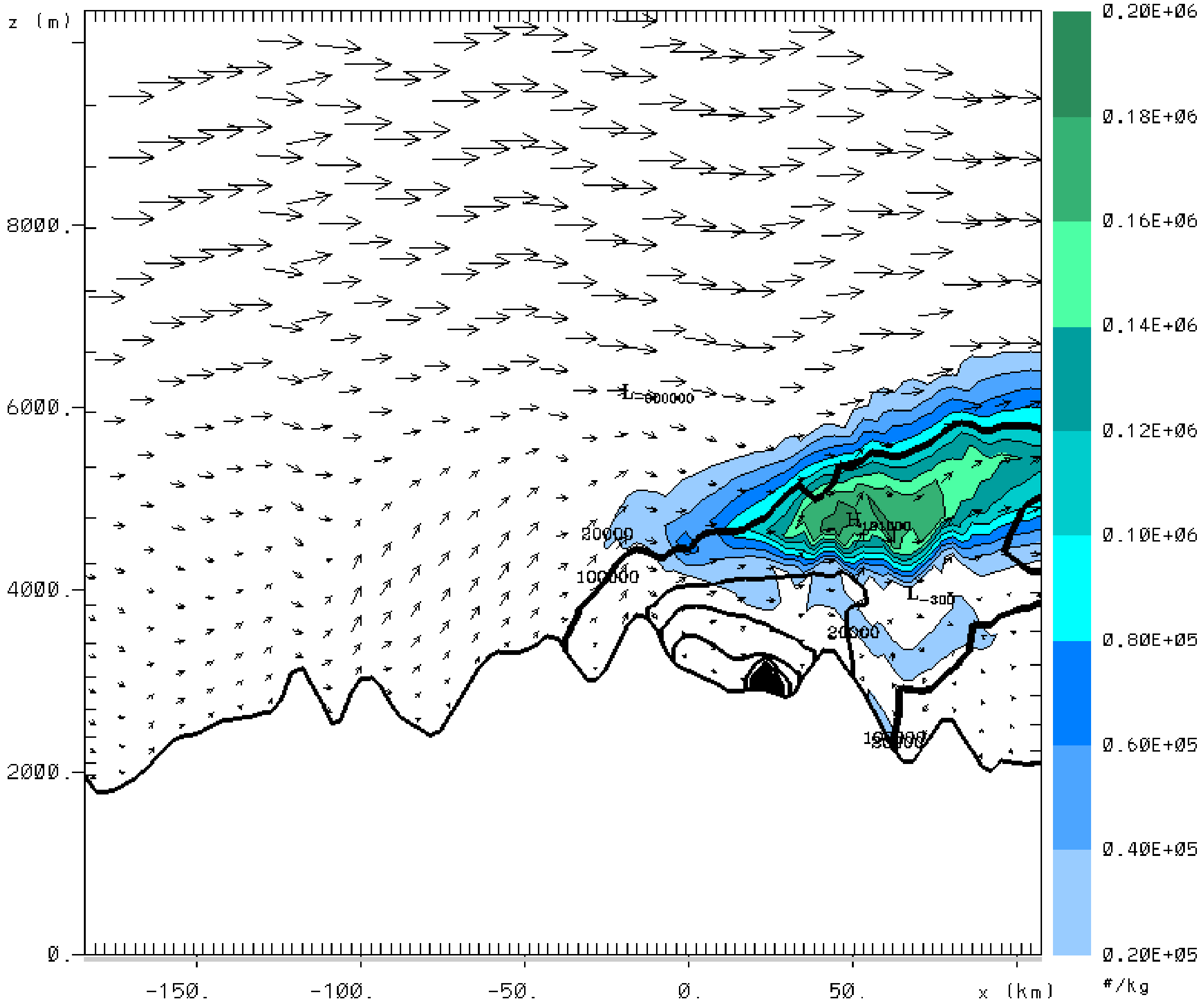
Init 02/04/03 0000 UTC sd4		grid 3			
z = 146.4 m	2003-02-05-0000.00 UTC	min	max	inc	lab*
contours	ifn2-conc (#/kg)	-7.198	0.6120E+07	0.2500E+06	1e 0
contours	topo (m)	1494.	3837.	300.0	1e 0
vectors →	3 m/s horiz	0.3034	12.34		

Figure A3.1. Available seeded IFN concentration (color contours) in lowest model layer, zoomed in to the target area (peach colored dashed outline). Topographic contours (black) are at 300-m intervals, and wind vectors are drawn at every 3rd grid point. Generators are located at yellow plusses and labeled with the yellow identifier adopted for the 2003-2004 season.



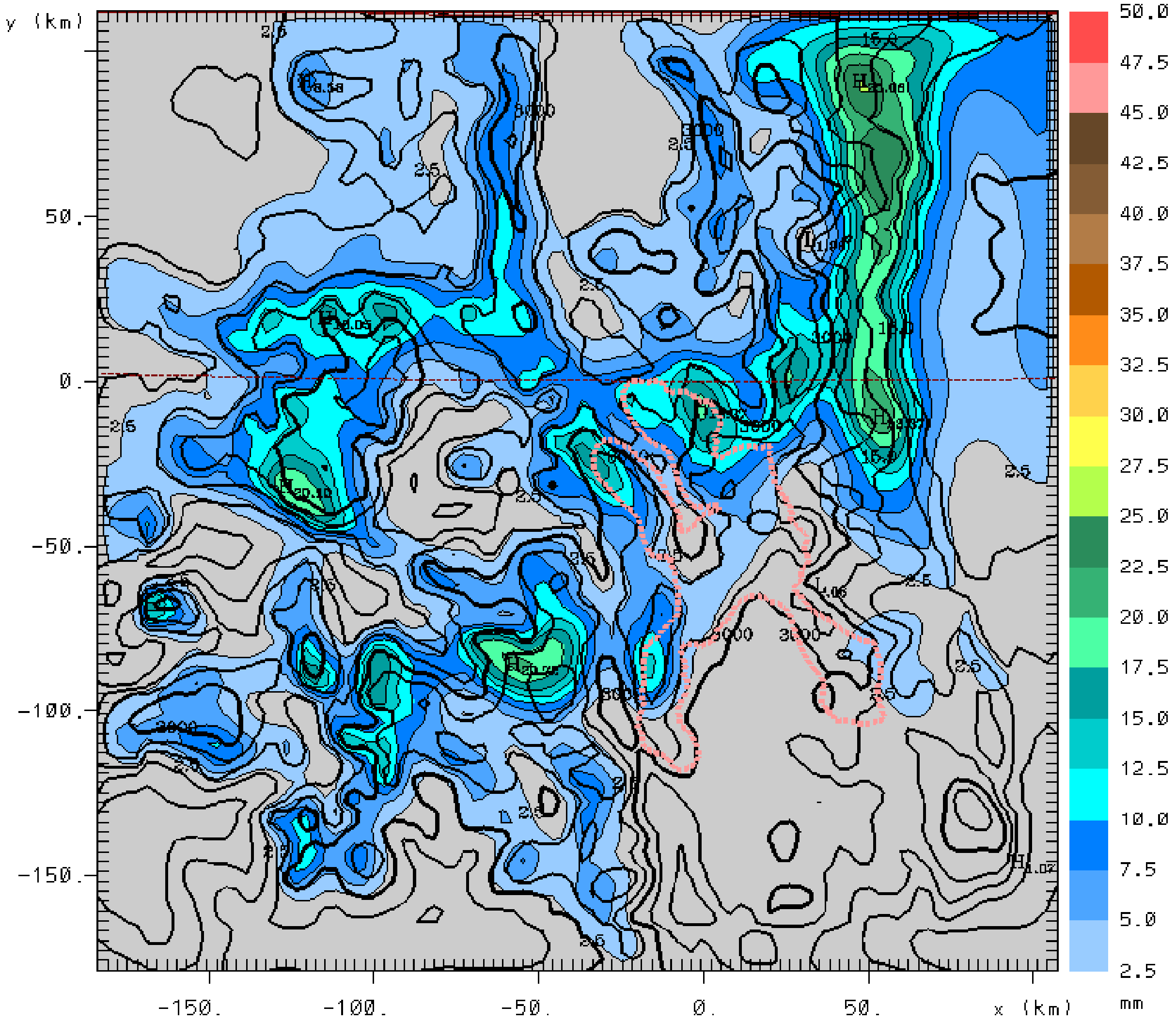
Init 02/04/03	0000 UTC sd4	grid 3			
z = 146.4 m	2003-02-05-0000.00 UTC	min	max	inc	lab*
contours	vertint act2 (#/m 2)	-1512.	0.2009E+09	0.2000E+08	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0
vectors →	3 m/s horiz	0.2063E-01	12.34		

Figure A3.2. Vertically integrated concentration of activated seeded IFN (color contours) over entire 3-km model grid. Topography, wind vectors, and target area are as in Figure A3.1.



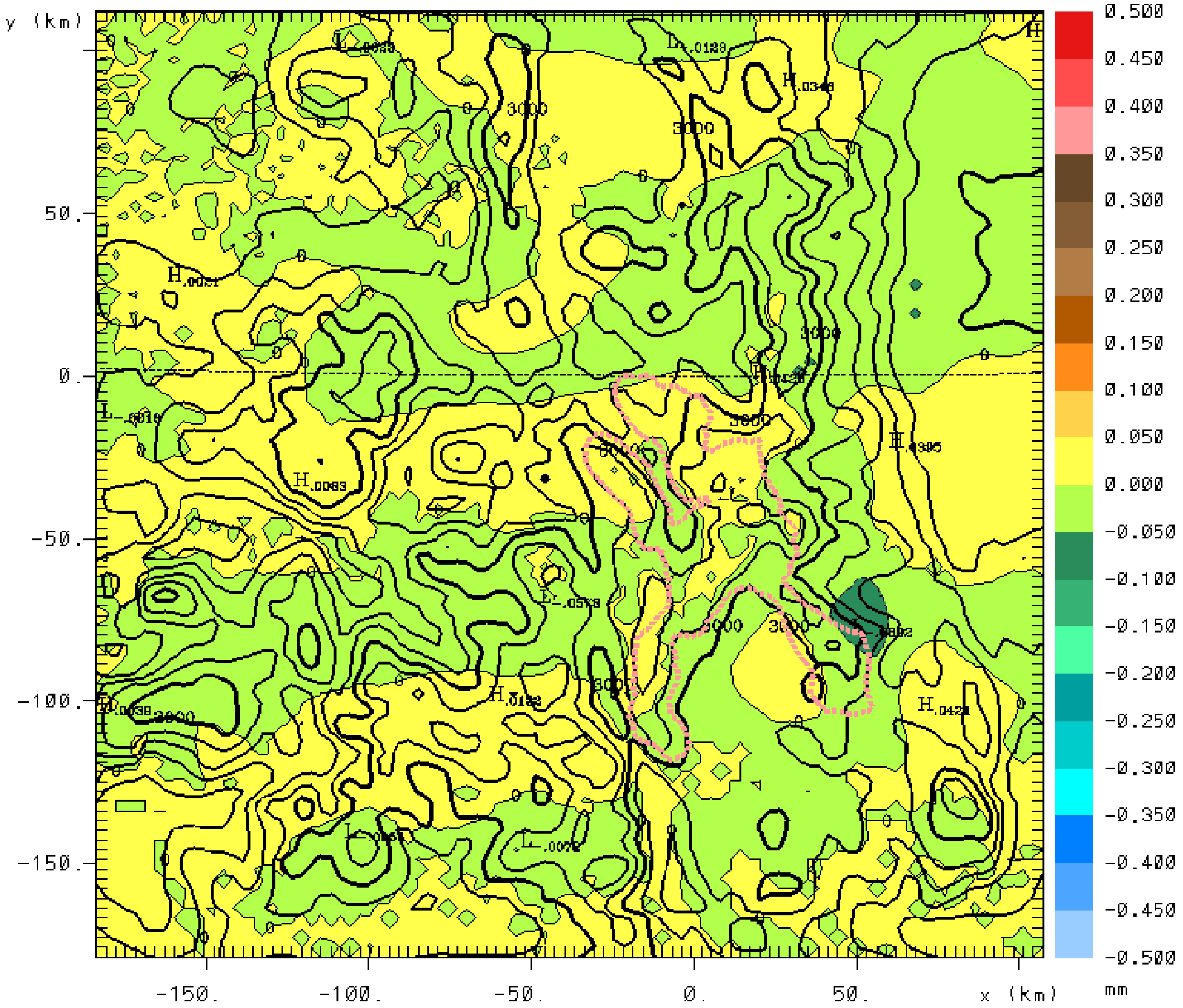
Init 02/04/03 0000 UTC sd4		grid 3			
y = -83. km	2003-02-05-0000.00 UTC	min	max	inc	lab*
contours	act2-conc (#/kg)	-305.3	0.1910E+06	0.2000E+05	1e 0
contours	ifn2-conc (#/kg)	-124.1	0.3041E+07	0.3000E+06	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.8184E-01	49.00		

Figure A3.3. West-to-east vertical cross section of activated seeded IFN (color contours) through the southern maximum in Figure A3.2. Indicated are topographic outline, available seeded IFN (black contours beginning at 10^5 per kg and at 3x10^5 increments), and wind vectors.



Init 02/04/03 0000 UTC ctl4		grid 3			
	2003-02-05-0800.00 UTC	min	max	inc	lab*
contours	precip 08-32h (mm)	0.000	25.06	2.500	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure A3.4. Simulated 24-hr precipitation for the control no-seed run.



Init 02/04/03 0000 UTC sd4		grid 3			
	2003-02-05-0800.00 UTC	min	max	inc	lab*
contours	sd-ctl precip 08-32h (mm)	-.1597	0.4263E-01	0.5000E-01	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure A3.5. Seed - Control 24-hr precipitation difference field. (1 mm = 0.03937 in)

APPENDIX 4

WESTERN WEATHER CONSULTANTS DAILY OPERATIONAL NOTES
January 15 – February 29, 2004
CSU RAMS Model Input in Operational Forecasts

Note on availability of RAMS – CSU switched the 00Z RAMS real-time forecast cycle to a faster PC cluster on January 10, 2004. Prior to this date, the RAMS output for use in preparing operational seeding forecasts was not timely or dependable. WWC (Larry Hjermstad) began adding comments on RAMS into his daily operational notes beginning January 15, 2004. These comments are hilited in yellow for easy reference.

Jan. 15, 2004 – possible weather opportunity for tonight – 700mb flow from NW but weak for orographics = 10kts or less moisture good but temp. = -3 degrees and fast to go to = -5 degrees (warm end of nuclei activation, model has = 1.5mm by 12Z on 16th in Vail and NRN Gore Range and or Cont. Div. West of Ark. River. Wind at sfc basically up-valley 2-5kts – very weak orog. Will not op. due to 2 inversions on GJT sounding at 16-00Z. One sfc to 7,000' MSL and another in base region of cloud layer. Temperature at cloud base also too warm for good nucleation. No ops. tonight.

Jan. 16, 2004 - (Start Seeding = 10 a.m.) – vertical winds – show precip. support for South Park during afternoon about 2 p.m. going into evening on west side of park. All other areas favorable for precip. (used accum. Precip., wind flow-Sfc) integrated vertical moisture, vertical velocity. Also 700 mb same parameters. 00Z (Didn't keep old stuff while new was processing) this really hurts for details. Need to change - would like precip. totals for short time segments - like 6 hrly. to see change in storm amounts. Very weak wind fields on a light NNE gradient building into area.

Jan. 17, 2004 – no weather for 48 hours….no info. on model outputs.

Jan. 18, 2004 – no Wx for 48 hrs 00Z.…..no output available….out to 48 hours from 00Z data at 10 p.m. – no history saved from previous data. NCEP data has possible start of precip. San Juan Mtn. and into central mountains by 12Z on Tuesday.

Jan. 19, 2004 – look at 19-00Z data has precip. into Gore range, Vail, Ark, Ind Pass, Cont. Div. & Loveland Pass at 00Z on 20th and Western Northern Park Co. Observation & mountain cams show no activity. Winds or precip. chart are light but favorable direction – no stability probs. indicated in mtns. with some low level inversion of 5,000 – 7,000 msl to West. Looks like the target area is the central point of precip. in the area (like a low center) precip. rate – best SW Park Co, Ind. Pass, (use close in generators) vert. velocities – some good for vert. Velocities around Hoosier Pass & SW Park Co. Not much good storm sustenance in So.

Park, spotty Vail, Blue River ok to best in Arkansas region Vertical velocity cross sections might indicate an inversion that would separate mtn. top vert. velocities from surface flow. Maybe better total system tomorrow morning from start 8 a.m. to over Vail, Gore. Vail ends 3 p.m.; Blue River about 8 p.m. New 00z data. Looked better than earlier and as a result I added generators in South Park and Upper Blue.

Jan. 20, 2004 – fcst on schedule…winds look like they could become more Easterly from 12 Z & 18Z maps during daytime hours – may have to shut off all generators West of Cont. Div. At 00Z data time 7:00 p.m., RAMS is down – can't access for comparisons with new NEC product using NECP new 00Z data. NCEP confirms Easterly winds on west side of divide in a gross scale but I needed the micro scale verification of RAMS. The NECP precip. fast looks to move the precip. out of the Blue River Valley too fast as Raobs at Riverton, Wy and 700 mb has large low level area of moisture to move into North Central Colo. through tonight into a.m. The RAMS handled the moisture field and wind field & precip. better than NCEP last night. RAMS still down at 11:30 p.m. Good night!

Jan. 21, 2004 - RAMS still down @ 7 a.m. Forecast on schedule all central colo. mtns. programs – stopped seeding 6-7 a.m. Wx has moved out. Scattered cold Cu in San Juans – continue seeding in San Juan till 6 p.m. Wednesday p.m. Off to Santa Fe – cloud seeding workshop – no weather expected.

Jan. 22, 2004 - missing

Jan. 23, 2004 – no Wx - start of set up to run of new PC cluster. No weather expected till about midnight.

Jan. 24, 2004 – RAMS still down 8 a.m. NCEP Model analysis shows precip. & potential favorable conditions moving into San Juans about 062 – 1-25-04 and into Western Central program by 12Z , 1-25-04. RAMS still down for "moving of equipment" to set up new cluster (Ray email). Model up and running 11:30 p.m. has precip. into area Vail & West Cont. Div. At 1 a.m. – looks fast as radar is at least showing 4-5 hrs. more delay – we will see targeting direction for 7 a.m. turn on right on target 260 degrees to 270 degrees. No inversions, good vert. Vel. + values for mixing. Total Condenrate look low of .5 to 1 at 12Z – I am expecting about 2.7 gm/kg water.

Jan. 25, 2004 – also looked at 700 mb temps. for first time – they need to go down to –15 degrees C. Winds are on track west bcmg. NW at noon and precip. is just getting started 13Z to 14Z across region with generator turn on at 7 a.m. about 14Z. The wind fields are strong enough over all across that mixing & diffusion will not be a problem through seed end time of 10 p.m. 1-25-04.

Jan. 26, 2004 – Mon. - too cold for operations until poss. Tuesday night – with warm air advection – minimal moisture initial look at data indicates possible start to next precip. for Tuesday evening 27th.

Jan. 27, 2004 – Using sfc precip., timing of precip. starts in Vail/Fri. p.m. area about 9 p.m. and Middle Park about midnight. Sfc winds 10k west with a SW 5K twitch in the North Gore Kremling region. No night activity in So. Park. Leadville to Twin Lks. Ok – Buena Vista? Decreasing precip. rate, verifying no precip. at Buena Vista & South Park. Ray/CSU is to expand the temp. field at 700mb to go down to –16 degrees C. Evening – models continues to show precip. start early morning to late night about 5 a.m.…call for generator starts when operators get up about 6:15 – 7 a.m. – go till Thursday p.m. 29th.

Jan. 28, 2004 – all models verify precip. into 29th and no activity into South Park. Also doubtful precip. got into lower Ark River Valley around Buena Vista. Winds mainly Westerly with a SW twitch around Kremling in a.m.…gens. there go on about noon with WNW bcmg. NW wind into night. No problems indicated for seeding dispersion of AgI – precip. amounts to be light with no cold air advection but temps. in a good operating range of –6 to –9 degrees C. RAMS continues to be too warm (about 6 degrees) on 700 mb temps. as compared to Wx Svc Maps. (29th 00z) – model info. ok but satellite shows breaks in clouds but should be good band of snow mid. to 6 a.m. into 29th. Winds and stability parameters ok for seed through night. No RAMS tonight.

Jan. 29, 2004 – **12Z** most of precip. activity on Cont. Div. & Gore Range. Little activity in Ark River Basin except near Leadville. Moisture looks to thin out after sunset and will use that time 5-7 p.m. to have generators go off. Precip. for 30th will likely move North as weak ridge spreads over Central Rockies. Tomorrow should be no activity till possibly late night, unless cold air turns S causing light snow to continue. Will check tonight. Interesting NECP has minimum activity at 00Z over project while RAMS has maximum activity, both have very light continuing through night. On 48 hours out, RAMS has precip. ending & NCEP has next batch moving in. Who's right? **00Z** New NECP has light precip. continuing all night breaking up about 10 a.m.. Its 9 p.m. and the late maps from RAMS are causing a problem. Not in at 9 p.m. which is getting late if gen. calls are needed. I am starting to use precip. rates rather than accum. Precip. to see more where the activity is and how heavy. I like the 6-hr blocks of total precip. from NECP. I'd better let generator go off as I expect minimal moisture – GJT sounding and satellite does not verify any lower clouds only middle level clds. The "Break" between the two Wx systems verified very well.

Jan. 30, 2004 – morning no weather. Evening forecast for timing of start of precip – best estimate about mid 07Z to 08Z 1 a.m. for Gore Range & Freemont Pass about 1 to 1 1/2 hr. earlier for Fry/ Pan. – Independence area. Precip. in the So. Park to begin mid morning on Saturday 31st and late morning in Ark Valley and look real good for amounts. The circulation looks like a bullseye low in the head of Arkansas Basin. This is almost a can't miss from all generators in the network. Temps in good range about -6 degrees C bcmg. -12 degrees C or colder. Western generators on at 9 p.m.

Jan. 31, 2004 – forecast right on schedule. Great circulation with low developing near Leadville. All precip. on schedule. Precip. amounts this morning greater than expected by Avalanche Center (seeding effect? smile). Wind targeting and moisture hold good into Sunday morning 8-10 a.m. then temperatures turn cold (bcmg. Colder than -15 degrees C so shut down seeding.

Note by WWC – with the apparent RAMS error in forecasting temps at 700 mb level – how can the RAMS model properly forecast precip amounts – especially precip. amounts associated with seeding when the model is about 6-8 degrees too warm and we need the colder temps. to activate the AgI nuclei??? We need to get this corrected before final precip. runs are made and especially before seeding runs are made. **Note this comment as this is a real problem**.

Feb. 1, 2004 – morning. Temps. got colder to –15 degrees C about 6 hours faster than expected – otherwise forecast on track – seeding off this morning from 8 a.m. west to 11 a.m. East & South. Evening – no operations – too cold. Still temp. problems on the RAMS.

Feb. 2, 2004 – RAMS model shows too much precip. still hanging in the target areas for evening. Next system expected in area morning of Feb. 3. Likely probs. are associated with continuing temps. problem. Precip. in the San Juan shows (SW flow) to be in at 11 p.m. Monday evening and well into target area mainly Vail, Gore & Fry /Pan.

Feb. 3, 2004 – Have question about the circulation shown by RAMS flow at 700 mb which shows a low over the center of target area when 700mb NWS Map and models show almost a straight South flow across all of the mountain region of Western Colo. I am choosing not to use Northern generators with this discrepancy as CSU model shows Northernly flow into a low which I question is existing or will likely developed since the main synoptic low is over central Utah. I used some of the circulation guidance mainly in the Upper Arkansas and South Park region. Right now with this storm system the NCEP guidance is more what is being observed and is doing well on the precipitation timing & intensity. I did use the RAMS 700 mb wind guidance on the selection of generators West of the Gore Range (close in) and in the Frying Pan. & Aspen area. Evening forecast looks like with the RAMS circulation, that Beaver Creek will have a huge dump of snow (I don't believe it will happen) as the RAMS continues the low circulation centered from Leadville to Minturn. I just don't see how the North & Westerly flows can ocure at RAMS 700 mb when the 700 mb NWS has a straight South flow over all of Western Colo. I printed data to have Cotton later look into this. On the 700 mb temp. map, the temperature field through the snow covered mountains shows a range of – 0 degrees to – 4 in the target area when the 700 mb NWS chart is indicating – 8 degrees C. How can the RAMS model do an accurate nucleation of AgI in a seeding test with temps. this far off???

Feb. 4, 2004 – Beaver Creek got 0" of snow along with Vail and Breckenridge, the low circ. in RAMS appears to be more of an imagination than reality. I will favor more the general geistrophic flow from NWS for targeting generator system until this exaggeration of RAMS flow is adjusted. I am sure this problem will lead to precip. forecasts will be generally way to high**.** The basic forecast is on schedule with the 700 mb low moving from 12Z Rifle to Ft. Lupton by 00Z bringing the shift to NW winds. Ray/CSU is working on the temp. problem and its erroneous association with too much circulation and precip. NW flow to continue into evening on 5th of Feb.

Feb. 5, 2004 – **12Z** Ray/CSU working on model during the day. The flow and moisture is near steady state from the North on the back side of a large closed low seeding is continuing on all North Northwest facing barriers. **00z evening –** the model is back up and looks much better for temps. There is still a slight heat island effect maybe 2-5 degrees warmer – but that may be adiabatic warming on the lee side of the hills. The wind flows look much better aligned with the gradient field and believable, allowing for some channeling in valleys and deflection around ranges. "Hurray" there still is a question in the derived low centers as there is maybe 5-6 degrees of warming at the circulation low center but not as wide spread as before. I would think with the most likely location of the precipitation would be in the low center region and that would cause "cooling" rather than warming. The output is better but still some questions. The cooling at 700 mb upstream looks good and "believable". This little extra heating is still driving too strong a low circulation, implying precip. in South Park which I don't believe.

Feb. 6, 2004 – Ray responded that **fixes were not in place** for run on Thursday evening even though some of the flow looked better. The weather is right on track with cleaning trend noted on satellite, ski cameras and field reports from operators. Next weather expected Saturday 2-7-04 night into Sunday morning. Will checkout new fix on RAMS tonight as first look at Sat/Sun weather.

Feb. 7, 2004 – RAMS being fixed – data not updated yet. NWS -eta model has moisture with short wave (SW) into Vail area about midnight with precip. about 2 a.m. with short wave passage about 3:30 a.m. (tough are for targeting with wind change at night.)

Feb. 8, 2004 – RAMS up and working – repairs look good (maybe still +2 to +3 degrees C to warm – suggested to Ray to put in constant of –2 degrees C on 700 mb map in mountain precip. > 12,000 MSL. Stream flows look much better and precip. rates are realistic – checked flow at Eagle Airport and it was right on – and no inversions. The operation is on track with snow expected into Sun. night to Mon. Likely shutting down generators around Buena Vista this evening on model output.

Feb. 9, 2004 – **12Z** Looking at wind pattern for today – looks good and temps. at 700 mb are about 2-3 degrees warmer than expected. Precip. rates are light but looking at the total precip. values for the orographic type flow the totals are about 15 mm or .6" this system is a classic orographic system and will likely have 15-20 hours of .01"/hr total between .15" to .20". I emailed Ray on this to check on the rates for a total, which I estimate, is about 3 times too high. This is likely still related to the temps. being about 2-3 degrees to warm at 700 mb. **00Z** evening forecast verifies clearing by about midnight. (Interesting add next morning was that only Breckenridge Ski area reported 1" of new snow with this part of the weather event – indicating that only the highest elevations got snow as was observed all day on the ski area cameras – and I may have over estimated the precip. at .15" above and likely it was less than .10" inches. and the model was likely 6 times too high.)

Feb. 10, 2004 – no weather this morning. Will start looking tonight for the possible Wx indicated for some time Wednesday. **00Z** data – precip. to start Wed. a.m. about noon and be more of an East slope storm but part my slip Southward along the West side of Cont. Div. and will be out of Colo. to South by Thursday p.m. The model shows that with the main short wave will be well up into Wyoming and the initial impact of the SW trough will be the back side with Northerly winds – maybe for Wed. night. Pre-trough winds all L/V and only very lightest velocity rates.

Feb. 11, 2004 – good example of cold air flooding over Colo. through-out the day – morning temps at 700 mb about –12 to –13 degrees C – RAMS shows at 00Z on 12th –6 to -8 degrees C when temps. are likely to be –14 to –16 degrees C. The wind flow looks acceptable and reasonable but likely the precip. rates may be too high. I will contact Ray to see if he can calibrate the model better using this weather situation. The flows on RAMS in So. Park look good consistent with observations of good snow across the So. Park. this morning around 8:30 – 9 a.m. **00Z** general forecast on schedule. Generators to go off about 9 p.m. tonight as temps. about -14 to –15 degrees C move into area. Looks cold for Thursday then warming for Friday. No ops for about 4-5 days. Maybe a NE Colorado System for Saturday (barely).

Feb. 12, 2004 – **12Z** clear & cold –16 degrees C to cold for man & beast. **00Z** first look at temps. at 700 mb is good. You can see adiabatic heating on front range and cold pools in Gunnison , Kremling, Steamboat areas. Things look the way they should.

Feb. 13, 2004 – Sunny all Friday and most of Saturday.

Note on model fixes: Final model Real-time Forecast fixes were implemented for the Feburary 14, 2004 run. After February 14 there were no additional changes made to the real-time forecast model.

Feb. 14, 2004 – **12Z** first look at precip. potential of short wave (SW) trough into Rockies for late tonight and Sunday with only a few spotty traces of precip with no seeding potential (dry air) from looking at precip. rates through out the region. Will check again tonight. **00Z** NCEP has some possible precip. in Northern Mtn., Steamboat to Vail by 12Z. Monday into 18Z - Nothing out of the initial SWT for Sunday.

Feb. 15, 2004 – NWS guidance has no precip. until about 3-6 a.m. Monday (most around Steamboat Springs) same into Vail , Gore and continue until about 3p.m. on 16th – appears light for intensity. RAMS from last night has spotty precip. Fry Pan., Vail, Loveland Pass about 1 a.m. on 16th staying on Westside of mtn. through 7 a.m. (Mar. 3-6 a.m.) again – Light intensity T – 1" about .05 total. I will visit with Ray on his color schemes and put maybe white dots in intervening colors for people like me that are slightly color blind. **00Z** - minimal system start time about 3 a.m. until about noon to 2 p.m. – out by 00Z with strong ridging pushing in. Basic orographics looking good and in the best temp. range (-6 to –11 degrees C) – but moisture on skimpy side – will not seed but just look on. Precip. max. Vail .23" Nast .30 Loveland about .23" – look 3 times high or more but good pattern.

Feb. 16, 2004 - Snow reports 7 a.m., Vail & BC = 0, Crested Butte = 0, Breck= 1", Steam about 1", Lov. about 1", all Aspen were 0, most others 0, this was the max. precip. time for the model. My estimate the max could be around 2-4 p.m. so will see tomorrow reports. **. **00Z** clearing on trend – next weather Wed. night late or Thursday morning – maybe closed low or deep through in 4 corners area. Initial glance indicates precip. at Ft. Collins – may start at some time as meeting at CSU. Wx in San Juan by 12Z Thurs. Model start time about midnight –2 p Wed.

Feb. 17, 2004 – snow report 7 a.m. AB-1", SC = 2, BR – 1, WP = 1 ½, Lov. – 1, Vail = 0. Nearly all ski areas were zero snow except highest sites on Cont. Div about 1" to 1.5". All other =0, model was closer **. **00Z** next precip starts about 2 a.m. or early morning of Feb 19 in San Juan and about 5 a.m. in Central Mountains with Southerly winds. Temps will be warm maybe +2 degrees C to start and we will likely start seeding between 9 a.m. to noon on 19th. (We should be eating our lunch at the 19th meeting in Ft. Collins and watching it start to snow = noon to 1 p.m.)

Feb. 18, 2004 – traveled to meeting. **00Z** the storm is going to move through much faster than first expected. This is verified in new 00Z RAMS run – evening of Feb. 18.

Feb. 19, 2004 – **12Z** maps show no potential for seeding in the pre-trough region so will start seeding in NW flow starting about noon on 19th and continue until 8 a.m. on 20th. The sfc & 700 MB wind flows and precip. indications appear to be in line with NWS data for these operations.

Feb. 20, 2004 – heading home – as new Wx system to begin moving into SW Colorado by about midnight. **00Z** data confirming Wx moving into SRN target area (UA & Central Mtn., So. Platte) about noonish to 2 p.m. with a first surge for the afternoon into evening.

Feb. 21, 2004 – with part of the low circulation around the head of the Arkansas Basin, there will be operations Saturday afternoon into early evening on West and North side of target area and in South Park and then more operations again all day Sunday until 10 p.m. or longer. In the Upper Arkansas Valley, the operations & precip. will hang on various sides of the valley and wind shift around with passage of the low over the region. (00_ 22nd) The model for tonight is about 180 degrees different than what was projected 24 hours ago. I checked across the So.Park from 2-21-00Z for 28 hours out and it is now 2-22-00Z only 4 hours out with exactly opposite pattern with precip. The precip is finally beginning when it should be ending – the NCEP shows So. Park on Eastern edge of precip with a more WSW wind, which usually isn't too productive. Now the New RAMS shows this too the earlier RAMS had NW wind shifting to NE & East by morning with a second batch of precip. scheduled. Now it looks like morning precip. may be out.

Feb. 22, 2004 – the models are picking up the moisture surges fairly well with reasonable timing. Looks like precip. will continue in Northern Mtns. until tonight and then be too thin to continue. Wx still continues in San Juans where I use the Grid 2 presentation and also get a better feel for the Wx in Colorado. – later the weather in San Juans also ended as the storm sunk way South and all low clouds ended.

Feb. 23, 2004 – **12Z** the Grid 2 model showed no substantial precip. for So. Park until late afternoon or early evening, also showed the return of precip. in the San Juans in early afternoon. The circulation and precip. amounts again appear too high and the model should be toned down by a factor of about 3. **00Z** data must have problems as nothing is available from RAMS at 10:30 p.m. this evening. The NWS data has precip. over area tonight into Tuesday. The RAMS has been a good help especially in So. Park & Arkansas Basin Region where there is little data. However, when there is Wx like tonight and RAMS is down it is a real drag.

Feb. 24, 2004 – RAMS holds precip. & clouds into Ark & South Platte Basins until this evening and over San Juan until early evening. Rates look high again but activity look consistent to synoptic Wx pattern. We look to shut down San Juan about 6 p.m. and Ark about 10 p.m. as of this morning. Will update at 18Z from new NWS info. satellite and radar look good.

Feb. 25, 2004 – precip. done for a day or so next poss. precip. on Thursday night about 9 p.m. in San Juans and maybe miss the North projects. RAMS not available for now will evaluate in morning of 26th.

Feb. 26, 2004 – NCEP shows precip. in by 10 p.m. Thursday night in WRN San Juan and all over areas by 12Z on 27 and around Aspen area on Southerly flow. Evening 00Z Old RAMS starts precip. in San Juan by 8 p.m. in Animas drainage tonight and holding on Southerly flow through 00z on 28th. I need to check temps. to get a good start seed time with – 3 degrees C and cooling. Winds 200 degrees entire time – precip. in Holy Cross to start midnight and move into Arkansas Valley to start 2 p.m. through 00Z /28th. Precip. snow amount in San Juan about .10" in 12 hr. maybe another .1" in next 12 hr. RAMS says 3.5 mm in 12 hr. or about .15" – not bad comparison and .4 in. in 24 hrs.

Feb. 27, 2004 – southerly flow holding most of moisture over eastern Utah and WRN Colorado. The models seem to handle precip. in the larger massive or E-W barriers better than channeled flow like up Ark Valley. Spotty precip on WRN edge of target South West of Vail (Aspen Area) first then moving into Ark. Valley. **00Z** not much change but enough valley channeling to turn on Aspen area for Upper Arkansas maybe – Ark. Valley first thing in morning & So. Park later morning Sat.

Feb. 28, 2004 – the temp. charts seem to be a lot more realistic – but there is still a tendency for slight low center circulation around heavy mtn. precip. in a region with convergence and some exaggeration of precip. amounts. I think the model can now be calibrated against observed precip. amounts to put in some adjustment CONSTANT. 12Z info. close to schedule on timing of low center through mountain. Used the surface wind timing to operate generators in Upper most Blue River Basin – in retrospect it might have been better to used more the 700 mb wind directions as they changed more favorable about 4 hours later.

Feb. 29, 2004 - Forecast on schedule – moisture holding in into Monday morning but getting shallower and amounts dropping off. The temperatures at 700mb are looking great.

OOZ Fcst. The RAMS 14th hour forecast is available about 10pm in evening– if RAMS speeds were about twice as fast I (Larry) could make calls for morning turn on fairly accurate the evening before with much more reliability. I usually don't call generator operators after 10pm and usually I would make about 30 calls and needs the time from 8:45-9:45 pm to call. The detail from RAMS helps in identifying all the seeding conditions much better than before (in General) but there have been bad times too.

APPENDIX 5

SNOTEL Observed & Model Control Simulated 24-hr Precipitation

Contents

Data Set One – 30 SNOTEL Sites Used in MRBP Study

Data Set Two – 31 SNOTEL Sites Not Used in MRBP Study

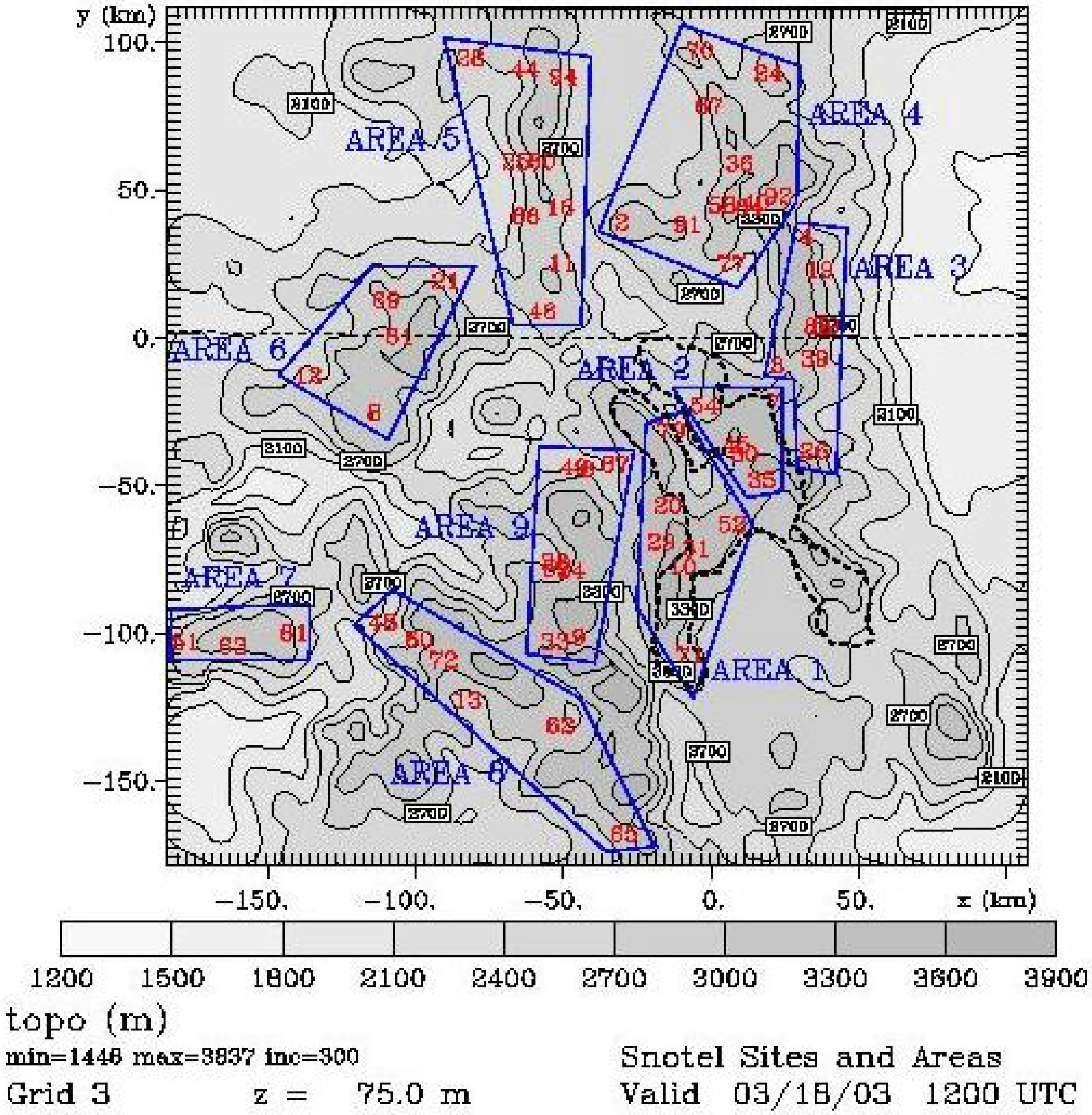


Figure 5.1. The 61 SNOTEL sites used in project evaluations on RAMS Grid 3, grouped into Areas 1-9, with shaded topography and Target Area boundary.

Areas with the 30 MRBP Study Sites
Area 1: Western Target Area (7 sites)
Area 2: Eastern Target Area (5 sites)
Area 4: Northern Front Range (7 sites)
Area 5: Park Range (6 sites)
Area 6: Flattops (5 sites)

Areas with the 31 non-MRBP Study Sites
Area 3: Eastern Front Range (7 sites)
Area 4: Northern Front Range (4 sites)
Area 5: Park Range (3 sites)
Area 7: Grand Mesa (3 sites)
Area 8: West-Central Rockies (6 sites)
Area 9: North-Central Rockies (8 sites)

Data Set One
30 SNOTEL Sites Used in MRBP Study

Summary of Model Control Run Precipitation Simulations vs Snotel Observations at 30 Snotel sites for 30 Operational Cloud Seeding Days Selected for the Multivariate Randomized Block Permutation Study

Rank by Difference	Date	30-site average 24-hr precip. (mm)			M/S Ratio	Wind Regime
		Model	Snotel	Difference		
1	40222	19.29	1.52	17.77	12.69	SSW
2	40102	25.55	11.60	13.95	2.20	WSW
3	31221	14.74	3.64	11.10	4.05	TROPA
4	31110	21.28	10.58	10.70	2.01	WSW
5	31226	14.20	3.98	10.22	3.57	TROPA
6	31215	16.63	6.52	10.11	2.55	NNW
7	31208	20.71	11.68	9.03	1.77	TROPA
8	40131	14.09	6.10	7.99	2.31	TROPA
9	40224	10.86	3.39	7.47	3.20	SSW
10	31117	20.35	13.21	7.14	1.54	WNW
11	31126	11.93	5.00	6.93	2.39	WNW
12	31122	12.32	6.10	6.22	2.02	TROPA
13	40208	9.50	3.81	5.69	2.49	TROPA
14	40103	13.65	8.30	5.35	1.64	WSW
15	40204	11.09	5.76	5.33	1.93	NNW
16	31114	10.07	5.42	4.65	1.86	WSW
17	40229	13.87	9.48	4.39	1.46	NNW
18	31227	7.88	3.89	3.99	2.03	TROPA
19	31103	13.02	9.06	3.96	1.44	SSW
20	31213	8.96	5.93	3.03	1.51	WNW
21	40129	5.58	3.22	2.36	1.73	WNW
22	40205	5.25	3.05	2.20	1.72	NNW
23	31230	6.11	5.67	0.44	1.08	WSW
24	31127	2.28	1.86	0.42	1.23	NNW
25	31111	5.52	5.16	0.36	1.07	WNW
26	40128	3.47	3.73	-0.26	0.93	W
27	31118	2.30	2.79	-0.49	0.82	NW
28	31105	4.06	6.52	-2.46	0.62	SW
29	31125	3.33	5.93	-2.60	0.56	W
30	31107	0.09	2.88	-2.79	0.03	SW
	Total	327.98	175.78	152.20	**1.87**	

1 mm = 0.03937 in.

Model 30-day Control Run Precipitation (mm) for the 30 MRBP Study Sites

Date	Area 01 - Western Target Area (7 stns)							Area 02 - Eastern Target Area (5 stns)				
ymmdd	79	20	52	29	31	10	71	54	7	45	30	35
31103	6.99	8.45	2.43	9.87	6.17	9.13	1.77	11.14	8.63	13.04	9.64	5.24
31105	0.85	1.51	0.10	2.01	0.89	1.29	0.00	0.75	1.05	5.42	4.59	2.26
31107	0.03	0.08	0.01	0.65	0.16	0.38	0.00	0.00	0.00	0.31	0.24	0.08
31110	4.88	17.98	4.18	19.31	7.27	10.53	0.63	13.06	10.30	18.97	17.41	9.62
31111	1.95	5.39	0.52	5.90	1.74	3.41	0.03	4.89	4.00	8.35	8.18	3.77
31114	3.83	8.77	2.05	11.11	3.39	5.85	0.02	8.05	6.93	12.22	11.37	6.79
31117	9.14	15.24	10.09	18.06	9.60	13.30	1.30	20.47	18.22	22.99	20.85	17.40
31118	0.25	1.09	2.49	2.85	0.86	0.92	0.01	3.00	1.54	2.23	1.81	1.23
31122	7.84	11.88	7.22	12.37	8.74	9.25	0.79	14.79	11.20	9.84	8.20	6.96
31125	1.27	3.42	1.13	3.97	2.59	3.94	0.03	1.00	2.27	4.03	3.95	3.16
31126	6.03	12.80	7.71	15.21	10.99	13.47	0.84	16.97	14.16	15.57	14.36	10.76
31127	0.48	1.92	2.07	3.04	1.19	1.46	0.08	3.54	1.93	2.41	2.01	1.42
31208	15.43	15.70	17.98	20.59	13.62	11.10	1.79	31.01	40.26	23.03	23.15	31.45
31213	1.25	7.93	3.02	10.50	3.54	5.53	0.01	3.76	2.96	10.60	10.22	6.47
31215	6.27	14.50	14.53	17.97	11.73	12.73	4.76	23.86	19.15	19.23	16.49	13.59
31221	6.93	15.59	13.97	16.16	17.06	14.72	4.84	9.09	9.31	7.87	6.86	6.56
31226	8.25	8.13	4.43	6.96	6.34	7.75	4.96	8.29	10.07	11.13	8.42	6.02
31227	5.62	5.43	2.70	5.52	4.12	5.60	0.65	10.98	9.56	11.01	10.07	8.01
31230	0.77	1.33	0.01	2.97	0.98	1.72	0.00	0.03	0.17	2.85	2.70	0.93
40102	17.29	22.12	10.64	24.95	18.83	24.15	7.08	20.98	18.74	26.52	25.36	17.72
40103	12.56	13.66	8.16	14.15	11.22	14.57	4.54	17.96	12.37	13.58	12.72	12.27
40128	0.46	2.53	0.43	4.32	0.88	1.25	0.00	1.99	1.15	3.38	3.32	1.67
40129	0.31	2.98	2.89	6.08	1.08	1.81	0.00	5.36	2.15	5.21	4.46	2.91
40131	12.80	15.93	28.29	17.03	21.57	21.48	25.83	12.73	18.37	16.64	17.41	26.02
40204	12.60	15.07	15.75	14.65	11.90	12.24	7.35	14.06	13.79	10.18	9.66	11.53
40205	6.19	5.52	6.78	7.81	5.60	4.08	0.09	12.38	9.59	6.00	4.56	3.56
40208	2.09	12.82	7.73	11.97	7.69	7.37	0.22	10.15	6.38	8.98	7.90	6.92
40222	11.38	34.57	40.98	36.83	35.58	28.87	14.06	18.38	38.62	41.59	44.95	53.40
40224	20.31	20.68	11.37	22.02	17.47	21.58	11.84	18.40	5.78	12.20	9.72	8.92
40229	3.93	12.34	10.97	17.40	11.01	14.54	0.61	15.71	11.13	13.93	12.38	10.91
Total	187.98	315.36	240.63	362.23	253.81	284.02	94.13	332.78	309.78	359.31	332.96	297.55

Model 30-day Control Run Precipitation (mm) for the 30 MRBP Study Sites

Area 04 - Northern Front Range (7 stns)							Area 05 - Park Range (6 stns)					
36	92	40	58	91	2	77	80	25	16	66	11	46
16.87	15.99	14.86	17.53	10.12	10.55	3.56	37.40	21.20	17.30	13.14	6.12	7.32
10.59	8.66	9.31	12.12	3.57	7.50	1.71	11.41	9.68	4.93	7.04	2.40	0.83
0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.04	0.00	0.01	0.00	0.00	0.00
31.19	27.63	24.88	33.09	18.44	31.58	12.92	46.27	46.95	24.82	41.36	18.06	14.61
11.90	6.23	5.82	9.56	0.91	4.95	1.43	18.25	9.77	8.47	8.08	3.24	0.72
18.33	10.03	11.00	18.69	5.06	9.37	6.81	29.50	26.22	14.68	20.55	5.64	1.89
27.18	16.95	17.53	28.22	9.92	23.45	6.59	45.13	30.14	29.59	32.88	18.65	12.55
4.89	1.64	2.78	6.25	0.77	1.09	1.08	3.90	5.84	1.89	9.13	1.14	0.82
16.32	19.21	16.14	17.99	14.11	12.45	8.24	13.01	12.13	12.10	22.34	11.14	10.54
7.29	5.28	5.29	7.54	2.64	5.42	2.64	11.51	3.75	5.32	2.39	1.78	0.14
12.76	7.13	7.22	11.74	2.30	8.39	2.92	19.72	20.73	12.33	24.06	9.89	10.10
4.49	2.06	2.72	6.00	1.34	1.65	0.63	3.42	4.84	2.24	8.40	1.53	0.95
21.89	24.85	23.05	33.45	31.92	23.81	23.61	16.78	12.38	16.28	24.59	14.48	11.80
14.72	8.47	9.93	15.28	2.59	10.91	3.27	22.74	26.15	12.88	20.64	8.97	3.62
22.36	14.71	15.74	25.75	12.80	14.50	5.45	16.51	16.26	15.96	33.06	15.44	11.27
17.31	19.27	15.10	17.19	10.82	17.68	4.71	20.35	20.66	17.28	22.35	14.53	8.23
8.95	10.43	9.54	12.45	8.68	12.26	2.95	25.10	20.02	15.80	16.18	11.27	11.13
9.00	4.42	4.98	9.33	2.20	5.84	2.13	13.16	13.51	8.65	19.19	6.49	6.76
10.81	7.01	6.74	10.16	2.52	8.92	1.12	28.39	31.79	12.65	16.78	4.06	1.27
32.56	24.37	22.92	29.14	14.63	23.47	27.04	54.11	33.30	32.63	31.05	14.25	21.95
14.41	13.74	12.67	15.24	6.67	9.51	9.48	22.23	16.48	12.80	16.30	8.95	5.93
5.89	2.05	3.66	6.11	0.58	3.87	0.74	10.85	14.42	4.88	13.18	2.14	0.64
10.57	4.10	5.77	11.95	1.00	3.34	1.85	15.26	23.48	6.08	21.03	3.52	3.92
11.30	14.76	9.81	11.83	17.07	12.91	8.01	6.52	4.06	7.14	12.28	10.19	7.61
4.03	5.72	3.36	2.85	8.83	13.83	2.51	13.54	12.13	13.20	18.77	10.33	6.92
4.31	4.45	3.38	5.20	7.03	8.04	0.20	1.37	0.55	2.87	7.04	3.91	3.25
14.57	7.29	8.33	17.84	5.16	9.40	2.97	17.57	22.74	9.04	25.88	5.23	3.05
12.27	18.11	10.76	13.59	8.52	6.97	5.70	12.16	11.57	5.37	9.22	5.88	3.24
7.18	4.92	4.70	8.80	8.08	10.11	4.16	10.06	7.39	10.85	11.50	10.26	10.06
23.78	14.18	16.12	27.44	14.45	14.46	8.58	21.10	27.03	13.99	31.50	9.18	6.38

407.72	323.67	304.11	442.34	232.73	326.24	163.01	567.36	505.17	352.03	539.91	238.67	187.50

Model 30-day Control Run Precipitation (mm) for the 30 MRBP Study Sites

Area 06 - Flattops (5 stns)					Average	Date
21	69	81	12	8	30 Stns	ymmdd
3.53	21.93	18.97	12.17	49.58	13.02	31103
0.23	3.08	3.08	1.32	3.57	4.06	31105
0.00	0.03	0.06	0.01	0.57	0.09	31107
13.87	29.66	29.79	23.24	35.77	21.28	31110
0.94	5.97	6.74	2.95	11.46	5.52	31111
1.84	10.99	10.11	5.24	15.69	10.07	31114
15.48	29.75	28.07	27.25	34.66	20.35	31117
1.04	2.20	2.56	2.80	0.90	2.30	31118
12.27	13.36	13.28	18.45	17.38	12.32	31122
1.09	1.66	3.31	0.02	2.20	3.33	31125
11.60	16.58	16.59	9.79	15.05	11.93	31126
0.95	1.51	2.20	1.30	0.56	2.28	31127
17.91	22.32	18.65	22.35	16.24	20.71	31208
0.84	11.45	11.79	7.61	11.09	8.96	31213
19.81	22.60	23.88	22.60	15.23	16.63	31215
13.60	25.58	24.27	17.01	27.19	14.74	31221
14.30	25.81	32.58	36.67	61.15	14.20	31226
8.10	10.52	10.73	10.15	12.10	7.88	31227
0.08	6.34	4.26	6.26	9.71	6.11	31230
13.42	33.10	33.49	27.54	63.13	25.55	40102
10.86	21.18	18.72	19.48	27.16	13.65	40103
0.28	3.65	3.56	2.79	3.43	3.47	40128
1.28	5.44	6.03	3.22	4.35	5.58	40129
12.20	12.59	9.09	10.31	10.87	14.09	40131
12.04	15.82	11.99	19.51	8.71	11.09	40204
5.99	8.31	6.05	10.85	2.45	5.25	40205
4.51	9.77	10.48	12.10	8.96	9.50	40208
19.61	7.21	11.73	5.62	11.86	19.29	40222
9.95	8.56	10.01	3.25	5.57	10.86	40224
8.08	11.99	12.50	11.18	9.28	13.87	40229
					10.93	
235.70	398.96	394.57	353.04	495.87	327.98	Total

Snotel 30-day Observed Precipitation (mm) for the 30 MRBP Study Sites

Date	Area 01 - Western Target Area (7 stns)							Area 02 - Eastern Target Area (5 stns)				
ymmdd	79	20	52	29	31	10	71	54	7	45	30	35
31103	15.24	2.54	2.54	7.62	5.08	2.54	7.62	5.08	15.24	10.16	2.54	0.00
31105	7.62	5.08	5.08	5.08	2.54	2.54	0.00	7.62	12.70	5.08	2.54	0.00
31107	2.54	5.08	0.00	0.00	0.00	0.00	0.00	2.54	2.54	2.54	2.54	0.00
31110	10.16	5.08	0.00	0.00	2.54	2.54	0.00	7.62	10.16	7.62	7.62	5.08
31111	10.16	2.54	0.00	0.00	2.54	2.54	0.00	7.62	12.70	7.62	7.62	2.54
31114	7.62	10.16	5.08	5.08	2.54	2.54	0.00	2.54	12.70	2.54	7.62	2.54
31117	15.24	15.24	10.16	10.16	10.16	7.62	2.54	7.62	15.24	12.70	12.70	5.08
31118	2.54	2.54	5.08	2.54	2.54	2.54	0.00	0.00	2.54	5.08	0.00	5.08
31122	2.54	0.00	5.08	0.00	5.08	0.00	0.00	2.54	5.08	2.54	0.00	0.00
31125	0.00	2.54	0.00	2.54	2.54	2.54	0.00	5.08	7.62	5.08	2.54	5.08
31126	10.16	2.54	2.54	7.62	7.62	0.00	0.00	5.08	7.62	7.62	5.08	0.00
31127	2.54	0.00	5.08	2.54	0.00	2.54	0.00	0.00	2.54	2.54	0.00	0.00
31208	5.08	5.08	7.62	7.62	10.16	2.54	5.08	10.16	10.16	12.70	7.62	7.62
31213	2.54	7.62	5.08	5.08	2.54	7.62	2.54	5.08	5.08	5.08	2.54	7.62
31215	7.62	5.08	0.00	15.24	7.62	0.00	0.00	12.70	15.24	5.08	2.54	5.08
31221	2.54	2.54	0.00	0.00	0.00	0.00	0.00	2.54	2.54	0.00	2.54	0.00
31226	2.54	2.54	7.62	2.54	5.08	0.00	5.08	2.54	2.54	0.00	0.00	2.54
31227	5.08	2.54	0.00	5.08	2.54	0.00	0.00	2.54	7.62	2.54	2.54	2.54
31230	7.62	2.54	0.00	5.08	2.54	2.54	0.00	5.08	10.16	5.08	5.08	0.00
40102	17.78	7.62	2.54	10.16	7.62	7.62	5.08	15.24	17.78	15.24	20.32	7.62
40103	10.16	7.62	12.70	7.62	12.70	0.00	5.08	7.62	12.70	12.70	10.16	10.16
40128	0.00	5.08	0.00	7.62	0.00	0.00	2.54	0.00	7.62	0.00	2.54	2.54
40129	5.08	2.54	5.08	2.54	0.00	2.54	0.00	2.54	7.62	2.54	5.08	2.54
40131	7.62	7.62	12.70	5.08	12.70	7.62	7.62	5.08	7.62	10.16	7.62	12.70
40204	7.62	2.54	5.08	5.08	5.08	5.08	5.08	7.62	10.16	5.08	7.62	2.54
40205	2.54	0.00	2.54	2.54	5.08	0.00	0.00	5.08	7.62	5.08	0.00	0.00
40208	2.54	0.00	0.00	5.08	2.54	0.00	0.00	5.08	5.08	2.54	5.08	0.00
40222	2.54	2.54	5.08	0.00	5.08	2.54	0.00	0.00	2.54	2.54	5.08	0.00
40224	5.08	2.54	0.00	2.54	2.54	2.54	2.54	5.08	7.62	2.54	2.54	2.54
40229	7.62	7.62	5.08	10.16	2.54	2.54	0.00	5.08	10.16	20.32	10.16	5.08
Total	187.96	127.00	111.76	142.24	129.54	71.12	50.80	152.40	256.54	180.34	149.86	96.52

Snotel 30-day Observed Precipitation (mm) for the 30 MRBP Study Sites

Area 04 - Northern Front Range (7 stns)							Area 05 - Park Range (6 stns)					
36	92	40	58	91	2	77	80	25	16	66	11	46
10.16	10.16	0.00	2.54	2.54	7.62	0.00	40.64	20.32	10.16	20.32	7.62	5.08
10.16	5.08	7.62	7.62	2.54	5.08	5.08	17.78	12.70	5.08	10.16	5.08	2.54
2.54	2.54	7.62	5.08	5.08	7.62	2.54	5.08	2.54	7.62	2.54	2.54	2.54
7.62	15.24	10.16	10.16	5.08	15.24	12.70	35.56	17.78	12.70	12.70	5.08	5.08
5.08	12.70	10.16	5.08	2.54	5.08	5.08	15.24	2.54	10.16	5.08	2.54	0.00
5.08	7.62	2.54	5.08	2.54	10.16	2.54	15.24	5.08	7.62	7.62	2.54	0.00
10.16	7.62	5.08	5.08	0.00	17.78	2.54	40.64	17.78	30.48	20.32	12.70	7.62
2.54	5.08	5.08	0.00	0.00	5.08	0.00	10.16	0.00	7.62	5.08	2.54	2.54
10.16	10.16	0.00	2.54	12.70	10.16	0.00	10.16	15.24	5.08	22.86	7.62	5.08
10.16	7.62	5.08	5.08	2.54	10.16	0.00	25.40	12.70	15.24	10.16	5.08	2.54
2.54	2.54	2.54	2.54	0.00	5.08	0.00	15.24	5.08	12.70	7.62	7.62	5.08
5.08	2.54	0.00	0.00	2.54	0.00	0.00	10.16	2.54	2.54	7.62	0.00	0.00
7.62	15.24	10.16	7.62	5.08	12.70	2.54	22.86	27.94	10.16	30.48	10.16	7.62
7.62	5.08	7.62	7.62	7.62	7.62	5.08	7.62	5.08	7.62	7.62	2.54	2.54
0.00	5.08	0.00	5.08	2.54	5.08	0.00	5.08	12.70	5.08	33.02	0.00	0.00
7.62	0.00	7.62	7.62	2.54	0.00	0.00	10.16	7.62	5.08	10.16	5.08	0.00
0.00	2.54	2.54	0.00	0.00	0.00	0.00	5.08	5.08	7.62	5.08	2.54	0.00
0.00	0.00	0.00	0.00	0.00	7.62	0.00	12.70	7.62	12.70	12.70	5.08	0.00
10.16	7.62	7.62	7.62	2.54	7.62	5.08	15.24	10.16	10.16	7.62	0.00	0.00
10.16	12.70	15.24	12.70	7.62	10.16	10.16	20.32	15.24	7.62	7.62	2.54	7.62
7.62	7.62	5.08	10.16	7.62	7.62	7.62	5.08	7.62	2.54	12.70	5.08	5.08
0.00	5.08	5.08	2.54	2.54	7.62	2.54	5.08	17.78	7.62	2.54	5.08	2.54
2.54	7.62	5.08	5.08	0.00	5.08	2.54	5.08	2.54	5.08	2.54	2.54	2.54
0.00	5.08	5.08	2.54	2.54	0.00	7.62	2.54	7.62	0.00	10.16	0.00	0.00
5.08	10.16	2.54	5.08	5.08	2.54	2.54	0.00	7.62	0.00	17.78	2.54	5.08
2.54	10.16	2.54	2.54	7.62	7.62	0.00	2.54	2.54	0.00	7.62	0.00	2.54
0.00	5.08	0.00	0.00	0.00	0.00	0.00	17.78	15.24	10.16	10.16	2.54	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.54	2.54	2.54	0.00	0.00
5.08	0.00	2.54	5.08	2.54	2.54	0.00	5.08	2.54	5.08	0.00	2.54	2.54
22.86	2.54	7.62	15.24	10.16	10.16	10.16	17.78	15.24	12.70	25.40	7.62	5.08
170.18	190.50	142.24	147.32	104.14	193.04	86.36	401.32	287.02	238.76	337.82	116.84	81.28

Snotel 30-day Observed Precipitation (mm) for the 30 MRBP Study Sites

Area 06 - Flattops (5 stns)					Average	Date
21	69	81	12	8	30 Stns	ymmdd
0.00	20.32	7.62	7.62	22.86	9.06	31103
7.62	10.16	7.62	5.08	12.70	6.52	31105
2.54	2.54	2.54	2.54	2.54	2.88	31107
2.54	30.48	15.24	17.78	27.94	10.58	31110
0.00	5.08	2.54	0.00	10.16	5.16	31111
5.08	10.16	2.54	2.54	7.62	5.42	31114
10.16	25.40	17.78	15.24	25.40	13.21	31117
0.00	0.00	0.00	2.54	5.08	2.79	31118
10.16	12.70	5.08	10.16	10.16	6.10	31122
0.00	12.70	10.16	2.54	5.08	5.93	31125
7.62	7.62	5.08	0.00	5.08	5.00	31126
0.00	2.54	0.00	0.00	2.54	1.86	31127
15.24	20.32	20.32	17.78	15.24	11.68	31208
5.08	5.08	12.70	7.62	7.62	5.93	31213
7.62	12.70	7.62	12.70	5.08	6.52	31215
5.08	5.08	7.62	7.62	7.62	3.64	31221
2.54	12.70	2.54	0.00	38.10	3.98	31226
5.08	10.16	2.54	5.08	2.54	3.89	31227
2.54	10.16	2.54	5.08	12.70	5.67	31230
7.62	15.24	15.24	10.16	25.40	11.60	40102
7.62	7.62	12.70	10.16	10.16	8.30	40103
2.54	5.08	2.54	2.54	5.08	3.73	40128
0.00	2.54	2.54	2.54	2.54	3.22	40129
2.54	10.16	7.62	5.08	10.16	6.10	40131
2.54	7.62	7.62	17.78	2.54	5.76	40204
0.00	5.08	5.08	2.54	0.00	3.05	40205
2.54	10.16	2.54	5.08	5.08	3.81	40208
5.08	0.00	0.00	2.54	2.54	1.52	40222
10.16	2.54	5.08	5.08	5.08	3.39	40224
5.08	10.16	2.54	10.16	7.62	9.48	40229
					5.86	
134.62	292.10	195.58	195.58	302.26	**175.77**	Total

Difference: Model Control Precip. (mm) minus Snotel Observed Precip. (mm) for the 30 MRBP Study Sites

Date	Area 01 - Western Target Area (7 stns)							Area 02 - Eastern Target Area (5 stns)				
ymmdd	79	20	52	29	31	10	71	54	7	45	30	35
31103	-8.25	5.91	-0.11	2.25	1.09	6.59	-5.85	6.06	-6.61	2.88	7.10	5.24
31105	-6.77	-3.57	-4.98	-3.07	-1.65	-1.25	0.00	-6.87	-11.65	0.34	2.05	2.26
31107	-2.51	-5.00	0.01	0.65	0.16	0.38	0.00	-2.54	-2.54	-2.23	-2.30	0.08
31110	-5.28	12.90	4.18	19.31	4.73	7.99	0.63	5.44	0.14	11.35	9.79	4.54
31111	-8.21	2.85	0.52	5.90	-0.80	0.87	0.03	-2.73	-8.70	0.73	0.56	1.23
31114	-3.79	-1.39	-3.03	6.03	0.85	3.31	0.02	5.51	-5.77	9.68	3.75	4.25
31117	-6.10	0.00	-0.07	7.90	-0.56	5.68	-1.24	12.85	2.98	10.29	8.15	12.32
31118	-2.29	-1.45	-2.59	0.31	-1.68	-1.62	0.01	3.00	-1.00	-2.85	1.81	-3.85
31122	5.30	11.88	2.14	12.37	3.66	9.25	0.79	12.25	6.12	7.30	8.20	6.96
31125	1.27	0.88	1.13	1.43	0.05	1.40	0.03	-4.08	-5.35	-1.05	1.41	-1.92
31126	-4.13	10.26	5.17	7.59	3.37	13.47	0.84	11.89	6.54	7.95	9.28	10.76
31127	-2.06	1.92	-3.01	0.50	1.19	-1.08	0.08	3.54	-0.61	-0.13	2.01	1.42
31208	10.35	10.62	10.36	12.97	3.46	8.56	-3.29	20.85	30.10	10.33	15.53	23.83
31213	-1.29	0.31	-2.06	5.42	1.00	-2.09	-2.53	-1.32	-2.12	5.52	7.68	-1.15
31215	-1.35	9.42	14.53	2.73	4.11	12.73	4.76	11.16	3.91	14.15	13.95	8.51
31221	4.39	13.05	13.97	16.16	17.06	14.72	4.84	6.55	6.77	7.87	4.32	6.56
31226	5.71	5.59	-3.19	4.42	1.26	7.75	-0.12	5.75	7.53	11.13	8.42	3.48
31227	0.54	2.89	2.70	0.44	1.58	5.60	0.65	8.44	1.94	8.47	7.53	5.47
31230	-6.85	-1.21	0.01	-2.11	-1.56	-0.82	0.00	-5.05	-9.99	-2.23	-2.38	0.93
40102	-0.49	14.50	8.10	14.79	11.21	16.53	2.00	5.74	0.96	11.28	5.04	10.10
40103	2.40	6.04	-4.54	6.53	-1.48	14.57	-0.54	10.34	-0.33	0.88	2.56	2.11
40128	0.46	-2.55	0.43	-3.30	0.88	1.25	-2.54	1.99	-6.47	3.38	0.78	-0.87
40129	-4.77	0.44	-2.19	3.54	1.08	-0.73	0.00	2.82	-5.47	2.67	-0.62	0.37
40131	5.18	8.31	15.59	11.95	8.87	13.86	18.21	7.65	10.75	6.48	9.79	13.32
40204	4.98	12.53	10.67	9.57	6.82	7.16	2.27	6.44	3.63	5.10	2.04	8.99
40205	3.65	5.52	4.24	5.27	0.52	4.08	0.09	7.30	1.97	0.92	4.56	3.56
40208	-0.45	12.82	7.73	6.89	5.15	7.37	0.22	5.07	1.30	6.44	2.82	6.92
40222	8.84	32.03	35.90	36.83	30.50	26.33	14.06	18.38	36.08	39.05	39.87	53.40
40224	15.23	18.14	11.37	19.48	14.93	19.04	9.30	13.32	-1.84	9.66	7.18	6.38
40229	-3.69	4.72	5.89	7.24	8.47	12.00	0.61	10.63	0.97	-6.39	2.22	5.83

Total (mm)	**0.02**	**188.36**	**128.87**	**219.99**	**124.27**	**212.90**	**43.33**	**180.38**	**53.24**	**178.97**	**183.10**	**201.03**
Total (in)	**0.00**	**7.42**	**5.07**	**8.66**	**4.89**	**8.38**	**1.71**	**7.10**	**2.10**	**7.05**	**7.21**	**7.91**

Difference: Model Control Precip. (mm) minus Snotel Observed Precip. (mm) for the 30 MRBP Study Sites

Area 04 - Northern Front Range (7 stns)							Area 05 - Park Range (6 stns)					
36	92	40	58	91	2	77	80	25	16	66	11	46
6.71	5.83	14.86	14.99	7.58	2.93	3.56	-3.24	0.88	7.14	-7.18	-1.50	2.24
0.43	3.58	1.69	4.50	1.03	2.42	-3.37	-6.37	-3.02	-0.15	-3.12	-2.68	-1.71
-2.54	-2.53	-7.62	-5.07	-5.08	-7.61	-2.54	-5.04	-2.54	-7.61	-2.54	-2.54	-2.54
23.57	12.39	14.72	22.93	13.36	16.34	0.22	10.71	29.17	12.12	28.66	12.98	9.53
6.82	-6.47	-4.34	4.48	-1.63	-0.13	-3.65	3.01	7.23	-1.69	3.00	0.70	0.72
13.25	2.41	8.46	13.61	2.52	-0.79	4.27	14.26	21.14	7.06	12.93	3.10	1.89
17.02	9.33	12.45	23.14	9.92	5.67	4.05	4.49	12.36	-0.89	12.56	5.95	4.93
2.35	-3.44	-2.30	6.25	0.77	-3.99	1.08	-6.26	5.84	-5.73	4.05	-1.40	-1.72
6.16	9.05	16.14	15.45	1.41	2.29	8.24	2.85	-3.11	7.02	-0.52	3.52	5.46
-2.87	-2.34	0.21	2.46	0.10	-4.74	2.64	-13.89	-8.95	-9.92	-7.77	-3.30	-2.40
10.22	4.59	4.68	9.20	2.30	3.31	2.92	4.48	15.65	-0.37	16.44	2.27	5.02
-0.59	-0.48	2.72	6.00	-1.20	1.65	0.63	-6.74	2.30	-0.30	0.78	1.53	0.95
14.27	9.61	12.89	25.83	26.84	11.11	21.07	-6.08	-15.56	6.12	-5.89	4.32	4.18
7.10	3.39	2.31	7.66	-5.03	3.29	-1.81	15.12	21.07	5.26	13.02	6.43	1.08
22.36	9.63	15.74	20.67	10.26	9.42	5.45	11.43	3.56	10.88	0.04	15.44	11.27
9.69	19.27	7.48	9.57	8.28	17.68	4.71	10.19	13.04	12.20	12.19	9.45	8.23
8.95	7.89	7.00	12.45	8.68	12.26	2.95	20.02	14.94	8.18	11.10	8.73	11.13
9.00	4.42	4.98	9.33	2.20	-1.78	2.13	0.46	5.89	-4.05	6.49	1.41	6.76
0.65	-0.61	-0.88	2.54	-0.02	1.30	-3.96	13.15	21.63	2.49	9.16	4.06	1.27
22.40	11.67	7.68	16.44	7.01	13.31	16.88	33.79	18.06	25.01	23.43	11.71	14.33
6.79	6.12	7.59	5.08	-0.95	1.89	1.86	17.15	8.86	10.26	3.60	3.87	0.85
5.89	-3.03	-1.42	3.57	-1.96	-3.75	-1.80	5.77	-3.36	-2.74	10.64	-2.94	-1.90
8.03	-3.52	0.69	6.87	1.00	-1.74	-0.69	10.18	20.94	1.00	18.49	0.98	1.38
11.30	9.68	4.73	9.29	14.53	12.91	0.39	3.98	-3.56	7.14	2.12	10.19	7.61
-1.05	-4.44	0.82	-2.23	3.75	11.29	-0.03	13.54	4.51	13.20	0.99	7.79	1.84
1.77	-5.71	0.84	2.66	-0.59	0.42	0.20	-1.17	-1.99	2.87	-0.58	3.91	0.71
14.57	2.21	8.33	17.84	5.16	9.40	2.97	-0.21	7.50	-1.12	15.72	2.69	3.05
12.27	18.11	10.76	13.59	8.52	6.97	5.70	12.16	9.03	2.83	6.68	5.88	3.24
2.10	4.92	2.16	3.72	5.54	7.57	4.16	4.98	4.85	5.77	11.50	7.72	7.52
0.92	11.64	8.50	12.20	4.29	4.30	-1.58	3.32	11.79	1.29	6.10	1.56	1.30

237.54	**133.17**	**161.87**	**295.02**	**128.59**	**133.20**	**76.65**	**166.04**	**218.15**	**113.27**	**202.09**	**121.83**	**106.22**
9.35	**5.24**	**6.37**	**11.61**	**5.06**	**5.24**	**3.02**	**6.54**	**8.59**	**4.46**	**7.96**	**4.80**	**4.18**

Difference: Model Control Precip. (mm) minus Snotel Observed Precip. (mm) for the 30 MRBP Study Sites

Area 06 - Flattops (5 stns)					Average Difference		Date
21	69	81	12	8	**Avg (mm)**	**Avg (in)**	ymmdd
3.53	1.61	11.35	4.55	26.72	**3.96**	**0.16**	31103
-7.39	-7.08	-4.54	-3.76	-9.13	**-2.46**	**-0.10**	31105
-2.54	-2.51	-2.48	-2.53	-1.97	**-2.79**	**-0.11**	31107
11.33	-0.82	14.55	5.46	7.83	**10.69**	**0.42**	31110
0.94	0.89	4.20	2.95	1.30	**0.35**	**0.01**	31111
-3.24	0.83	7.57	2.70	8.07	**4.65**	**0.18**	31114
5.32	4.35	10.29	12.01	9.26	**7.15**	**0.28**	31117
1.04	2.20	2.56	0.26	-4.18	**-0.49**	**-0.02**	31118
2.11	0.66	8.20	8.29	7.22	**6.22**	**0.24**	31122
1.09	-11.04	-6.85	-2.52	-2.88	**-2.59**	**-0.10**	31125
3.98	8.96	11.51	9.79	9.97	**6.93**	**0.27**	31126
0.95	-1.03	2.20	1.30	-1.98	**0.42**	**0.02**	31127
2.67	2.00	-1.67	4.57	1.00	**9.03**	**0.36**	31208
-4.24	6.37	-0.91	-0.01	3.47	**3.03**	**0.12**	31213
12.19	9.90	16.26	9.90	10.15	**10.11**	**0.40**	31215
8.52	20.50	16.65	9.39	19.57	**11.10**	**0.44**	31221
11.76	13.11	30.04	36.67	23.05	**10.22**	**0.40**	31226
3.02	0.36	8.19	5.07	9.56	**3.99**	**0.16**	31227
-2.46	-3.82	1.72	1.18	-2.99	**0.44**	**0.02**	31230
5.80	17.86	18.25	17.38	37.73	**13.95**	**0.55**	40102
3.24	13.56	6.02	9.32	17.00	**5.36**	**0.21**	40103
-2.26	-1.43	1.02	0.25	-1.65	**-0.26**	**-0.01**	40128
1.28	2.90	3.49	0.68	1.81	**2.36**	**0.09**	40129
9.66	2.43	1.47	5.23	0.71	**7.99**	**0.31**	40131
9.50	8.20	4.37	1.73	6.17	**5.34**	**0.21**	40204
5.99	3.23	0.97	8.31	2.45	**2.20**	**0.09**	40205
1.97	-0.39	7.94	7.02	3.88	**5.69**	**0.22**	40208
14.53	7.21	11.73	3.08	9.32	**17.76**	**0.70**	40222
-0.21	6.02	4.93	-1.83	0.49	**7.47**	**0.29**	40224
3.00	1.83	9.96	1.02	1.66	**4.39**	**0.17**	40229
					5.07	**0.20**	
101.08	**106.86**	**198.99**	**157.46**	**193.61**	**152.20**		**Total (mm)**
3.98	**4.21**	**7.83**	**6.20**	**7.62**		**5.99**	**Total (in)**

Data Set Two
31 SNOTEL Sites Not Used in MRBP Study

Summary of Model Control Run Precipitation Simulations vs Snotel Observations at 31 Snotel sites for 31 non-MRBP Operational Cloud Seeding Days Not Used in the Multivariate Randomization Block Permutation Study

Rank by difference		31-site average 24-hr precip. (mm)			M/S Ratio	Wind Regime
	Date	**Model**	**Snotel**	**Difference**		
1	31208	27.17	11.55	15.62	2.35	TROPA
2	40222	16.67	2.70	13.97	6.17	SSW
3	40224	13.96	1.31	12.65	10.66	SSW
4	40131	18.15	5.82	12.33	3.12	TROPA
5	31221	15.84	4.51	11.33	3.51	TROPA
6	40102	28.57	17.94	10.63	1.59	WSW
7	31110	20.68	10.65	10.03	1.94	WSW
8	31122	14.51	4.51	10.00	3.22	TROPA
9	40229	13.75	6.06	7.69	2.27	NNW
10	40103	18.59	11.31	7.28	1.64	WSW
11	31226	12.78	6.15	6.63	2.08	TROPA
12	31117	17.65	11.06	6.59	1.60	WNW
13	31215	12.97	6.55	6.42	1.98	NNW
14	40204	13.59	7.21	6.38	1.88	NNW
15	40208	7.50	1.64	5.86	4.57	TROPA
16	31103	16.82	10.98	5.84	1.53	SSW
17	31227	6.24	2.54	3.70	2.46	TROPA
18	31114	8.40	4.92	3.48	1.71	WSW
19	31126	8.74	5.33	3.41	1.64	WNW
20	40205	4.88	2.62	2.26	1.86	NNW
21	40129	3.49	2.46	1.03	1.42	WNW
22	31111	5.03	4.34	0.69	1.16	WNW
23	31213	6.32	6.23	0.09	1.01	WNW
24	40128	2.36	2.38	-0.02	0.99	W
25	31118	1.13	1.80	-0.67	0.63	NW
26	31127	1.17	2.13	-0.96	0.55	NNW
27	31125	2.41	3.69	-1.28	0.65	W
28	31230	6.34	7.95	-1.61	0.80	WSW
29	31105	2.68	4.34	-1.66	0.62	SW
30	31107	0.09	2.46	-2.37	0.04	SW
	Total	328.48	173.14	155.34	**1.90**	

1 mm = 0.03937 in.

Model 30-day Control Run Precipitation (mm) for the 31 non-MRBP Study Sites

Date	Area 03 - Eastern Front Range (7 stns)							Area 04 - Northern Front Rrange (4 stns)			
ymmdd	4	19	59	83	39	3	26	70	24	67	64
31103	12.21	5.42	8.40	13.83	5.49	8.39	0.82	10.59	13.46	17.57	12.56
31105	6.69	2.90	1.83	4.38	1.08	0.63	0.03	4.96	2.77	12.42	7.73
31107	0.01	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31110	15.83	7.23	5.19	11.56	5.02	11.62	0.48	21.42	18.66	36.68	22.12
31111	7.47	4.80	3.77	8.19	4.16	3.78	0.04	3.98	4.33	7.51	5.11
31114	10.87	6.40	5.10	10.60	6.66	9.95	0.16	7.63	7.25	15.48	10.48
31117	11.88	6.98	6.68	12.99	8.82	12.07	4.34	12.64	15.99	25.58	15.93
31118	1.81	0.70	0.48	1.36	1.19	3.25	0.00	0.02	0.05	1.06	2.80
31122	24.56	31.22	25.31	25.65	19.91	15.44	15.53	13.37	17.13	13.17	15.31
31125	5.29	3.14	2.21	4.09	1.57	0.50	0.17	3.43	2.88	7.77	4.86
31126	4.98	3.23	4.86	9.02	9.39	14.21	3.65	5.86	6.87	15.81	6.81
31127	1.18	0.57	0.60	1.37	1.32	3.61	0.05	0.06	0.68	1.96	2.75
31208	29.80	46.50	65.62	67.59	66.33	39.18	73.21	24.70	17.57	21.68	22.54
31213	7.31	3.63	2.59	6.29	3.89	4.05	0.03	2.70	1.76	12.60	8.62
31215	4.29	3.28	5.61	10.05	9.68	18.71	3.39	9.55	19.39	19.89	15.47
31221	18.73	21.93	20.65	22.86	16.84	6.49	12.28	11.88	15.36	16.63	12.89
31226	6.94	3.28	3.80	5.56	5.09	5.80	2.04	14.11	9.57	14.72	8.80
31227	3.47	2.67	2.83	5.43	4.68	8.74	2.05	1.80	2.58	6.91	4.80
31230	11.91	6.30	2.43	5.53	0.85	0.15	0.01	6.87	3.63	14.93	4.91
40102	30.21	32.60	19.72	28.86	13.22	13.74	4.00	19.93	18.77	28.79	21.54
40103	14.46	18.75	22.84	26.90	16.59	14.76	4.49	11.37	9.63	12.32	12.05
40128	2.61	1.00	0.68	1.88	1.39	4.58	0.01	1.26	0.07	6.85	3.05
40129	4.04	1.72	1.01	2.91	1.97	5.30	0.00	4.66	3.70	12.58	4.95
40131	23.09	32.29	36.27	34.24	29.02	11.10	30.18	11.94	24.77	15.26	8.61
40204	10.46	12.89	14.63	13.18	13.35	9.17	18.07	13.39	7.77	3.52	2.68
40205	0.88	1.65	3.66	3.77	4.21	9.42	11.19	9.00	7.83	5.07	2.77
40208	5.84	4.88	3.25	6.65	3.74	7.57	0.21	5.03	10.13	15.33	8.29
40222	22.78	34.33	44.81	44.32	45.82	24.34	73.20	12.51	13.38	13.07	9.59
40224	3.55	3.69	4.85	7.31	4.82	5.51	3.17	8.40	5.18	10.24	4.78
40229	7.14	5.42	6.28	11.32	8.39	12.76	1.17	12.43	22.38	28.25	16.09
Total	310.29	309.41	325.96	407.71	314.49	284.82	263.97	265.49	283.54	413.65	278.89

Model 30-day Control Run Precipitation (mm) for the 31 non-MRBP Study Sites

Area 05 - Park Range (3 stns)			Area 07 - Grand Mesa (3 stns)			Area 08 - West-Central Rockies (6 stns)					
28	44	94	61	63	51	48	60	72	13	62	65
19.95	43.18	26.65	31.63	46.39	25.58	19.61	36.95	39.77	12.20	14.65	11.21
2.27	12.52	5.79	0.82	1.26	0.08	1.21	2.33	2.46	0.56	0.62	3.22
0.00	0.00	0.00	0.04	0.07	0.01	0.00	0.25	1.07	0.03	0.10	0.01
20.81	39.20	25.42	18.81	36.77	34.78	31.84	31.85	32.65	13.24	18.96	23.44
2.61	13.66	7.93	1.16	1.18	1.43	1.68	7.76	8.04	1.58	3.10	7.59
7.84	22.05	11.50	3.71	5.73	4.04	5.46	13.89	13.57	3.81	3.81	7.49
16.97	33.85	22.61	11.61	25.38	27.85	19.03	37.01	32.82	11.90	7.48	20.69
1.76	6.40	1.21	0.39	0.53	0.61	0.02	0.27	0.25	0.18	0.00	1.66
8.60	8.80	7.35	13.40	15.54	17.49	8.48	17.85	17.30	3.25	3.24	7.27
3.96	12.13	8.07	0.01	0.00	0.00	0.00	0.78	3.25	0.44	0.49	0.27
7.52	15.32	8.68	3.00	6.52	6.96	3.23	15.19	15.18	4.55	2.93	8.55
0.27	2.56	0.74	0.42	0.51	0.39	0.05	0.55	0.46	0.08	0.03	0.07
13.22	14.52	13.87	13.43	23.07	27.87	12.73	24.65	28.94	13.10	6.96	16.08
6.92	24.87	7.94	2.48	6.95	3.98	9.86	12.53	9.28	1.62	0.76	3.81
11.67	12.27	7.08	12.49	19.45	22.14	4.86	16.30	16.34	5.77	3.48	7.55
10.57	15.77	7.76	10.06	19.46	17.05	12.90	20.05	25.56	13.02	18.52	8.72
14.52	24.29	18.24	32.47	40.49	19.79	17.34	28.50	31.75	6.41	8.30	9.38
4.82	8.97	5.61	5.68	7.78	8.55	5.68	13.81	14.10	3.91	2.56	10.02
7.79	29.99	12.87	4.86	15.29	13.34	6.17	8.92	9.59	3.32	2.78	10.83
12.14	33.65	27.41	32.13	38.51	40.07	46.03	62.37	65.30	36.76	32.84	45.35
13.91	21.24	15.93	22.38	27.10	28.83	18.41	33.44	39.07	18.58	13.86	20.57
3.99	16.20	3.53	0.26	1.30	1.06	0.26	2.02	2.37	0.04	0.01	0.01
10.26	20.87	4.77	0.18	0.42	0.18	0.10	1.67	1.85	0.07	0.03	0.98
2.61	3.53	3.79	13.87	15.51	14.54	18.56	22.04	16.50	5.30	9.91	23.91
3.92	3.41	11.63	5.91	13.79	29.99	14.80	27.89	25.22	9.57	5.15	18.97
2.27	1.65	1.63	1.69	3.77	10.19	2.96	7.24	5.01	0.88	0.12	1.41
7.72	12.99	5.43	2.28	4.45	8.86	4.35	11.57	10.81	2.89	2.26	10.94
5.52	17.05	19.62	3.60	12.34	7.35	2.52	6.47	7.25	2.63	8.78	13.50
0.34	3.77	6.19	7.47	11.16	11.36	4.16	21.14	28.13	10.44	12.82	20.91
14.00	19.26	7.82	17.17	13.02	26.24	13.50	23.64	27.15	18.08	8.34	22.84
238.75	493.97	307.07	273.41	413.74	410.61	285.80	508.93	531.04	204.21	192.89	337.25

Model 30-day Control Run Precipitation (mm) for the 31 non-MRBP Study Sites

Area 09 - North-Central Rockies (8 stns)								Average	Date
87	49	6	38	57	34	9	33	31 Stns	ymmdd
7.37	4.65	5.15	10.27	9.85	12.57	17.37	17.76	16.82	31103
1.06	0.10	0.16	0.40	0.31	1.29	0.76	0.56	2.68	31105
0.01	0.00	0.00	0.05	0.04	0.32	0.48	0.36	0.09	31107
18.87	15.02	15.14	18.35	19.15	32.67	20.38	17.85	20.68	31110
6.24	3.91	4.37	5.37	5.67	9.42	5.39	4.64	5.03	31111
9.72	3.95	4.88	8.84	9.30	14.75	7.46	7.93	8.40	31114
18.04	8.18	10.14	18.56	19.28	28.30	20.64	22.86	17.65	31117
0.88	0.10	0.25	0.98	1.17	2.87	0.92	1.75	1.13	31118
10.10	14.32	15.09	11.01	11.70	16.30	12.66	13.51	14.51	31122
1.07	0.22	0.46	0.70	0.87	3.14	1.80	1.28	2.41	31125
13.27	7.68	9.05	9.65	9.49	16.48	11.39	11.55	8.74	31126
2.14	0.76	1.15	1.81	2.05	3.71	1.78	2.54	1.17	31127
15.89	18.22	19.33	18.12	20.15	27.58	18.25	21.47	27.17	31208
9.10	0.90	1.60	6.54	6.20	11.60	6.84	8.73	6.32	31213
12.38	8.03	10.42	17.06	19.29	25.60	23.64	27.03	12.97	31215
16.52	15.14	16.14	14.73	15.12	18.41	17.93	21.20	15.84	31221
5.84	1.75	2.95	6.88	6.25	7.83	16.78	16.64	12.78	31226
6.22	2.51	3.08	7.82	8.13	11.92	7.84	8.38	6.24	31227
1.18	0.09	0.14	1.48	1.36	3.53	2.89	2.50	6.34	31230
19.48	13.41	14.45	21.76	21.49	31.38	29.96	29.84	28.57	40102
17.16	16.63	16.63	10.97	11.70	19.02	23.09	23.65	18.59	40103
3.12	0.28	0.50	1.99	2.16	6.37	1.56	2.82	2.36	40128
3.55	0.24	0.56	2.76	3.05	7.91	1.98	3.88	3.49	40129
16.16	18.57	20.33	18.57	20.87	25.95	17.96	17.43	18.15	40131
17.76	15.39	16.14	15.38	15.73	21.08	13.03	17.45	13.59	40204
5.02	5.99	6.71	5.93	6.88	9.20	5.18	8.03	4.88	40205
15.12	6.21	8.12	7.62	8.24	14.98	7.53	9.08	7.50	40208
6.27	4.26	5.09	11.22	12.40	18.77	7.65	6.22	16.67	40222
39.43	27.48	34.38	23.06	24.01	35.78	27.49	21.66	13.96	40224
13.40	9.57	11.36	7.56	7.09	14.94	8.78	10.83	13.75	40229
								10.95	
312.37	223.56	253.77	285.44	299.00	453.67	339.41	359.43	328.47	Total

Snotel 30-day Observed Precipitation (mm) for the 31 non-MRBP Study Sites

Date	Area 03 - Eastern Front Range (7 stns)							Area 04 - Northern Front Range (4 stns)			
ymmdd	4	19	59	83	39	3	26	70	24	67	64
31103	17.78	2.54	5.08	15.24	2.54	15.24	15.24	12.70	12.70	7.62	2.54
31105	10.16	2.54	2.54	5.08	7.62	7.62	2.54	5.08	2.54	2.54	5.08
31107	2.54	2.54	0.00	0.00	2.54	0.00	0.00	2.54	7.62	5.08	7.62
31110	20.32	2.54	2.54	12.70	2.54	5.08	0.00	10.16	5.08	0.00	7.62
31111	10.16	7.62	10.16	12.70	12.70	10.16	0.00	0.00	5.08	2.54	2.54
31114	5.08	2.54	5.08	10.16	2.54	7.62	0.00	7.62	0.00	2.54	2.54
31117	7.62	2.54	2.54	12.70	7.62	5.08	0.00	10.16	7.62	5.08	5.08
31118	10.16	2.54	2.54	5.08	5.08	2.54	0.00	2.54	2.54	0.00	0.00
31122	10.16	2.54	10.16	2.54	2.54	5.08	5.08	10.16	5.08	5.08	10.16
31125	5.08	5.08	5.08	7.62	2.54	2.54	0.00	5.08	0.00	0.00	2.54
31126	2.54	0.00	5.08	7.62	5.08	5.08	0.00	2.54	0.00	2.54	2.54
31127	0.00	5.08	2.54	5.08	2.54	2.54	2.54	2.54	2.54	0.00	27.94
31208	15.24	10.16	15.24	12.70	7.62	5.08	10.16	22.86	7.62	2.54	12.70
31213	7.62	2.54	0.00	7.62	2.54	2.54	2.54	2.54	10.16	5.08	5.08
31215	0.00	0.00	2.54	0.00	0.00	10.16	0.00	2.54	10.16	5.08	0.00
31221	2.54	0.00	0.00	0.00	0.00	0.00	0.00	5.08	5.08	5.08	2.54
31226	2.54	0.00	0.00	2.54	0.00	2.54	0.00	2.54	0.00	0.00	2.54
31227	0.00	0.00	5.08	2.54	0.00	0.00	0.00	0.00	0.00	0.00	2.54
31230	7.62	2.54	2.54	2.54	0.00	12.70	0.00	2.54	5.08	2.54	0.00
40102	15.24	12.70	10.16	15.24	10.16	12.70	0.00	15.24	15.24	10.16	10.16
40103	15.24	7.62	12.70	5.08	7.62	10.16	5.08	5.08	7.62	7.62	7.62
40128	2.54	0.00	0.00	2.54	2.54	2.54	0.00	2.54	2.54	0.00	2.54
40129	5.08	0.00	0.00	0.00	2.54	5.08	2.54	2.54	0.00	0.00	2.54
40131	7.62	7.62	15.24	15.24	5.08	5.08	7.62	2.54	0.00	2.54	2.54
40204	5.08	5.08	10.16	10.16	5.08	7.62	5.08	5.08	5.08	2.54	0.00
40205	0.00	0.00	7.62	2.54	2.54	0.00	0.00	10.16	7.62	7.62	0.00
40208	0.00	0.00	2.54	2.54	0.00	0.00	0.00	5.08	5.08	0.00	2.54
40222	2.54	0.00	5.08	5.08	10.16	0.00	5.08	0.00	0.00	0.00	0.00
40224	0.00	2.54	0.00	2.54	0.00	5.08	0.00	0.00	2.54	0.00	0.00
40229	5.08	0.00	2.54	5.08	2.54	7.62	0.00	2.54	15.24	0.00	5.08

Total	195.58	88.90	144.78	190.50	114.30	157.48	63.50	160.02	149.86	83.82	134.62

Snotel 30-day Observed Precipitation (mm) for the 31 non-MRBP Study Sites

Area 05 - Park Range (3 stns)			Area 07 - Grand Mesa (3 stns)			Area 08 - West-Central Rockies (6 stns)					
28	44	94	61	63	51	48	60	72	13	62	65
15.24	25.40	25.40	5.08	7.62	2.54	10.16	20.32	30.48	7.62	7.62	10.16
7.62	5.08	15.24	2.54	2.54	2.54	2.54	2.54	5.08	0.00	0.00	0.00
2.54	5.08	0.00	2.54	2.54	7.62	2.54	0.00	5.08	2.54	0.00	2.54
15.24	27.94	35.56	10.16	20.32	7.62	17.78	12.70	22.86	7.62	7.62	15.24
0.00	5.08	7.62	0.00	2.54	0.00	0.00	5.08	12.70	0.00	2.54	2.54
5.08	5.08	10.16	2.54	10.16	5.08	2.54	12.70	15.24	10.16	2.54	0.00
17.78	22.86	27.94	12.70	20.32	12.70	10.16	17.78	27.94	7.62	7.62	10.16
2.54	2.54	7.62	0.00	0.00	0.00	0.00	0.00	5.08	0.00	0.00	0.00
12.70	7.62	10.16	0.00	2.54	5.08	7.62	5.08	0.00	0.00	0.00	2.54
5.08	7.62	12.70	0.00	0.00	0.00	0.00	2.54	5.08	2.54	2.54	0.00
7.62	7.62	10.16	5.08	12.70	7.62	2.54	10.16	20.32	10.16	2.54	5.08
0.00	2.54	2.54	0.00	0.00	0.00	2.54	0.00	0.00	0.00	0.00	2.54
12.70	7.62	10.16	15.24	22.86	17.78	17.78	20.32	27.94	12.70	0.00	7.62
5.08	12.70	10.16	5.08	5.08	12.70	10.16	7.62	15.24	7.62	2.54	2.54
2.54	2.54	0.00	10.16	38.10	15.24	5.08	7.62	15.24	5.08	0.00	2.54
5.08	7.62	10.16	10.16	12.70	7.62	7.62	7.62	12.70	7.62	5.08	5.08
7.62	5.08	7.62	20.32	45.72	25.40	12.70	12.70	20.32	7.62	2.54	0.00
7.62	2.54	5.08	0.00	2.54	2.54	5.08	7.62	12.70	2.54	0.00	0.00
7.62	12.70	17.78	10.16	12.70	5.08	17.78	12.70	20.32	12.70	10.16	5.08
15.24	17.78	25.40	20.32	40.64	27.94	15.24	22.86	50.80	20.32	17.78	38.10
2.54	2.54	5.08	12.70	15.24	10.16	22.86	22.86	38.10	15.24	12.70	12.70
2.54	7.62	12.70	0.00	0.00	0.00	0.00	2.54	2.54	0.00	0.00	2.54
10.16	10.16	7.62	2.54	2.54	0.00	0.00	0.00	2.54	5.08	2.54	0.00
0.00	0.00	0.00	7.62	12.70	7.62	12.70	7.62	10.16	0.00	7.62	15.24
10.16	5.08	5.08	0.00	5.08	25.40	12.70	5.08	10.16	17.78	5.08	12.70
2.54	2.54	2.54	0.00	2.54	0.00	2.54	12.70	2.54	0.00	0.00	0.00
10.16	5.08	5.08	0.00	5.08	0.00	0.00	2.54	0.00	0.00	0.00	0.00
0.00	5.08	0.00	2.54	17.78	12.70	2.54	0.00	5.08	0.00	0.00	0.00
2.54	2.54	2.54	0.00	2.54	0.00	2.54	0.00	5.08	0.00	0.00	5.08
10.16	10.16	5.08	2.54	17.78	17.78	12.70	5.08	10.16	7.62	2.54	2.54

205.74	243.84	297.18	160.02	342.90	238.76	218.44	246.38	411.48	170.18	101.60	162.56

Snotel 30-day Observed Precipitation (mm) for the 31 non-MRBP Study Sites

Area 09 - North-Central Rockies (8 stns)								Average	Date
87	49	6	38	57	34	9	33	31 Stns	ymmdd
12.70	7.62	10.16	7.62	10.16	5.08	5.08	5.08	10.98	31103
7.62	7.62	5.08	2.54	2.54	5.08	2.54	2.54	4.34	31105
2.54	2.54	2.54	2.54	0.00	2.54	0.00	0.00	2.46	31107
17.78	15.24	12.70	5.08	2.54	5.08	2.54	0.00	10.65	31110
12.70	5.08	5.08	0.00	0.00	0.00	0.00	0.00	4.34	31111
12.70	5.08	5.08	2.54	0.00	0.00	0.00	0.00	4.92	31114
12.70	10.16	10.16	12.70	5.08	12.70	10.16	7.62	11.06	31117
2.54	2.54	0.00	0.00	0.00	0.00	0.00	0.00	1.80	31118
5.08	7.62	2.54	0.00	0.00	2.54	0.00	0.00	4.51	31122
5.08	5.08	5.08	2.54	2.54	5.08	5.08	10.16	3.69	31125
5.08	5.08	2.54	2.54	0.00	5.08	5.08	5.08	5.33	31126
2.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.13	31127
12.70	10.16	2.54	5.08	10.16	12.70	2.54	7.62	11.55	31208
2.54	5.08	5.08	10.16	7.62	7.62	5.08	5.08	6.23	31213
10.16	15.24	10.16	5.08	7.62	7.62	0.00	12.70	6.55	31215
2.54	0.00	2.54	5.08	0.00	5.08	0.00	5.08	4.51	31221
5.08	0.00	2.54	2.54	0.00	0.00	0.00	0.00	6.15	31226
10.16	2.54	2.54	0.00	0.00	0.00	0.00	5.08	2.54	31227
10.16	10.16	12.70	5.08	7.62	7.62	2.54	7.62	7.95	31230
20.32	22.86	20.32	12.70	10.16	15.24	7.62	7.62	17.94	40102
15.24	15.24	17.78	7.62	12.70	10.16	0.00	7.62	11.31	40103
5.08	2.54	0.00	5.08	0.00	5.08	2.54	5.08	2.38	40128
0.00	2.54	2.54	0.00	0.00	2.54	2.54	2.54	2.46	40129
7.62	7.62	5.08	0.00	0.00	5.08	0.00	2.54	5.82	40131
10.16	12.70	10.16	0.00	2.54	5.08	0.00	7.62	7.21	40204
7.62	0.00	0.00	0.00	5.08	2.54	0.00	0.00	2.62	40205
5.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.64	40208
2.54	5.08	0.00	0.00	0.00	0.00	0.00	2.54	2.70	40222
5.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	40224
12.70	7.62	5.08	0.00	0.00	2.54	2.54	7.62	6.06	40229
								5.77	
243.84	193.04	160.02	96.52	86.36	132.08	55.88	116.84	**173.13**	Total

Difference: Model Control Precip. (mm) minus Snotel Observed Precip. (mm) for the 31 non-MRBP Study Sites

Date	Area 03 - Eastern Front Range (7 stns)							Area 04 - Northern Front Range (4 stns)			
ymmdd	4	19	59	83	39	3	26	70	24	67	64
31103	-5.57	2.88	3.32	-1.41	2.95	-6.85	-14.42	-2.11	0.76	9.95	10.02
31105	-3.47	0.36	-0.71	-0.70	-6.54	-6.99	-2.51	-0.12	0.23	9.88	2.65
31107	-2.53	-2.53	0.00	0.02	-2.54	0.00	0.00	-2.54	-7.62	-5.08	-7.62
31110	-4.49	4.69	2.65	-1.14	2.48	6.54	0.48	11.26	13.58	36.68	14.50
31111	-2.69	-2.82	-6.39	-4.51	-8.54	-6.38	0.04	3.98	-0.75	4.97	2.57
31114	5.79	3.86	0.02	0.44	4.12	2.33	0.16	0.01	7.25	12.94	7.94
31117	4.26	4.44	4.14	0.29	1.20	6.99	4.34	2.48	8.37	20.50	10.85
31118	-8.35	-1.84	-2.06	-3.72	-3.89	0.71	0.00	-2.52	-2.49	1.06	2.80
31122	14.40	28.68	15.15	23.11	17.37	10.36	10.45	3.21	12.05	8.09	5.15
31125	0.21	-1.94	-2.87	-3.53	-0.97	-2.04	0.17	-1.65	2.88	7.77	2.32
31126	2.44	3.23	-0.22	1.40	4.31	9.13	3.65	3.32	6.87	13.27	4.27
31127	1.18	-4.51	-1.94	-3.71	-1.22	1.07	-2.49	-2.48	-1.86	1.96	-25.19
31208	14.56	36.34	50.38	54.89	58.71	34.10	63.05	1.84	9.95	19.14	9.84
31213	-0.31	1.09	2.59	-1.33	1.35	1.51	-2.51	0.16	-8.40	7.52	3.54
31215	4.29	3.28	3.07	10.05	9.68	8.55	3.39	7.01	9.23	14.81	15.47
31221	16.19	21.93	20.65	22.86	16.84	6.49	12.28	6.80	10.28	11.55	10.35
31226	4.40	3.28	3.80	3.02	5.09	3.26	2.04	11.57	9.57	14.72	6.26
31227	3.47	2.67	-2.25	2.89	4.68	8.74	2.05	1.80	2.58	6.91	2.26
31230	4.29	3.76	-0.11	2.99	0.85	-12.55	0.01	4.33	-1.45	12.39	4.91
40102	14.97	19.90	9.56	13.62	3.06	1.04	4.00	4.69	3.53	18.63	11.38
40103	-0.78	11.13	10.14	21.82	8.97	4.60	-0.59	6.29	2.01	4.70	4.43
40128	0.07	1.00	0.68	-0.66	-1.15	2.04	0.01	-1.28	-2.47	6.85	0.51
40129	-1.04	1.72	1.01	2.91	-0.57	0.22	-2.54	2.12	3.70	12.58	2.41
40131	15.47	24.67	21.03	19.00	23.94	6.02	22.56	9.40	24.77	12.72	6.07
40204	5.38	7.81	4.47	3.02	8.27	1.55	12.99	8.31	2.69	0.98	2.68
40205	0.88	1.65	-3.96	1.23	1.67	9.42	11.19	-1.16	0.21	-2.55	2.77
40208	5.84	4.88	0.71	4.11	3.74	7.57	0.21	-0.05	5.05	15.33	5.75
40222	20.24	34.33	39.73	39.24	35.66	24.34	68.12	12.51	13.38	13.07	9.59
40224	3.55	1.15	4.85	4.77	4.82	0.43	3.17	8.40	2.64	10.24	4.78
40229	2.06	5.42	3.74	6.24	5.85	5.14	1.17	9.89	7.14	28.25	11.01

Total (mm)	**114.71**	**220.51**	**181.18**	**217.21**	**200.19**	**127.34**	**200.47**	**105.47**	**133.68**	**329.83**	**144.27**
Total (in)	**4.52**	**8.68**	**7.13**	**8.55**	**7.88**	**5.01**	**7.89**	**4.15**	**5.26**	**12.99**	**5.68**

Difference: Model Control Precip. (mm) minus Snotel Observed Precip. (mm) for the 31 non-MRBP Study Sites

Area 05 - Park Range (3 stns)			Area 07 - Grand Mesa (3 stns)			Area 08 - West-Central Rockies (6 stns)					
28	44	94	61	63	51	48	60	72	13	62	65
4.71	17.78	1.25	26.55	38.77	23.04	9.45	16.63	9.29	4.58	7.03	1.05
-5.35	7.44	-9.45	-1.72	-1.28	-2.46	-1.33	-0.21	-2.62	0.56	0.62	3.22
-2.54	-5.08	0.00	-2.50	-2.47	-7.61	-2.54	0.25	-4.01	-2.51	0.10	-2.53
5.57	11.26	-10.14	8.65	16.45	27.16	14.06	19.15	9.79	5.62	11.34	8.20
2.61	8.58	0.31	1.16	-1.36	1.43	1.68	2.68	-4.66	1.58	0.56	5.05
2.76	16.97	1.34	1.17	-4.43	-1.04	2.92	1.19	-1.67	-6.35	1.27	7.49
-0.81	10.99	-5.33	-1.09	5.06	15.15	8.87	19.23	4.88	4.28	-0.14	10.53
-0.78	3.86	-6.41	0.39	0.53	0.61	0.02	0.27	-4.83	0.18	0.00	1.66
-4.10	1.18	-2.81	13.40	13.00	12.41	0.86	12.77	17.30	3.25	3.24	4.73
-1.12	4.51	-4.63	0.01	0.00	0.00	0.00	-1.76	-1.83	-2.10	-2.05	0.27
-0.10	7.70	-1.48	-2.08	-6.18	-0.66	0.69	5.03	-5.14	-5.61	0.39	3.47
0.27	0.02	-1.80	0.42	0.51	0.39	-2.49	0.55	0.46	0.08	0.03	-2.47
0.52	6.90	3.71	-1.81	0.21	10.09	-5.05	4.33	1.00	0.40	6.96	8.46
1.84	12.17	-2.22	-2.60	1.87	-8.72	-0.30	4.91	-5.96	-6.00	-1.78	1.27
9.13	9.73	7.08	2.33	-18.65	6.90	-0.22	8.68	1.10	0.69	3.48	5.01
5.49	8.15	-2.40	-0.10	6.76	9.43	5.28	12.43	12.86	5.40	13.44	3.64
6.90	19.21	10.62	12.15	-5.23	-5.61	4.64	15.80	11.43	-1.21	5.76	9.38
-2.80	6.43	0.53	5.68	5.24	6.01	0.60	6.19	1.40	1.37	2.56	10.02
0.17	17.29	-4.91	-5.30	2.59	8.26	-11.61	-3.78	-10.73	-9.38	-7.38	5.75
-3.10	15.87	2.01	11.81	-2.13	12.13	30.79	39.51	14.50	16.44	15.06	7.25
11.37	18.70	10.85	9.68	11.86	18.67	-4.45	10.58	0.97	3.34	1.16	7.87
1.45	8.58	-9.17	0.26	1.30	1.06	0.26	-0.52	-0.17	0.04	0.01	-2.53
0.10	10.71	-2.85	-2.36	-2.12	0.18	0.10	1.67	-0.69	-5.01	-2.51	0.98
2.61	3.53	3.79	6.25	2.81	6.92	5.86	14.42	6.34	5.30	2.29	8.67
-6.24	-1.67	6.55	5.91	8.71	4.59	2.10	22.81	15.06	-8.21	0.07	6.27
-0.27	-0.89	-0.91	1.69	1.23	10.19	0.42	-5.46	2.47	0.88	0.12	1.41
-2.44	7.91	0.35	2.28	-0.63	8.86	4.35	9.03	10.81	2.89	2.26	10.94
5.52	11.97	19.62	1.06	-5.44	-5.35	-0.02	6.47	2.17	2.63	8.78	13.50
-2.20	1.23	3.65	7.47	8.62	11.36	1.62	21.14	23.05	10.44	12.82	15.83
3.84	9.10	2.74	14.63	-4.76	8.46	0.80	18.56	16.99	10.46	5.80	20.30

33.01	**250.13**	**9.89**	**113.39**	**70.84**	**171.85**	**67.36**	**262.55**	**119.56**	**34.03**	**91.29**	**174.69**
1.30	**9.85**	**0.39**	**4.46**	**2.79**	**6.77**	**2.65**	**10.34**	**4.71**	**1.34**	**3.59**	**6.88**

Difference: Model Control Precip. (mm) minus Snotel Observed Precip. (mm) for the 31 non-MRBP Study Sites

Area 09 - North-Central Rockies (8 stns)								Average Difference		Date
87	49	6	38	57	34	9	33	**Avg (mm)**	**Avg (in)**	ymmdd
-5.33	-2.97	-5.01	2.65	-0.31	7.49	9.75	12.68	**5.76**	**0.23**	31103
-6.56	-7.52	-4.92	-2.14	-2.23	-3.79	-1.78	-1.98	**-1.66**	**-0.07**	31105
-2.53	-2.54	-2.54	-2.49	0.04	-2.22	-2.06	0.36	**-2.45**	**-0.10**	31107
1.09	-0.22	2.44	13.27	16.61	27.59	15.30	17.85	**9.94**	**0.39**	31110
-6.46	-1.17	-0.71	5.37	5.67	9.42	5.39	4.64	**0.69**	**0.03**	31111
-2.98	-1.13	-0.20	6.30	9.30	14.75	4.92	7.93	**3.40**	**0.13**	31114
5.34	-1.98	-0.02	5.86	14.20	15.60	7.94	15.24	**6.51**	**0.26**	31117
-1.66	-2.44	0.25	0.98	1.17	2.87	0.92	1.75	**-0.68**	**-0.03**	31118
5.02	6.70	12.55	11.01	11.70	13.76	12.66	13.51	**10.01**	**0.39**	31122
-4.01	-4.86	-4.62	-1.84	-1.67	-1.94	-0.74	-8.88	**-1.19**	**-0.05**	31125
8.19	2.60	6.51	7.11	9.49	11.40	8.85	6.47	**3.49**	**0.14**	31126
-0.40	0.76	1.15	1.81	2.05	3.71	1.78	2.54	**-0.96**	**-0.04**	31127
3.19	8.06	16.79	13.04	9.99	14.88	13.17	13.85	**15.53**	**0.61**	31208
6.56	-4.18	-3.48	-3.62	-1.42	3.98	-3.32	3.65	**-0.07**	**0.00**	31213
2.22	-7.21	0.26	11.98	11.67	17.98	18.56	14.33	**6.25**	**0.25**	31215
13.98	15.14	13.60	9.65	15.12	13.33	12.85	16.12	**11.17**	**0.44**	31221
0.76	1.75	0.41	4.34	6.25	7.83	14.24	16.64	**6.55**	**0.26**	31226
-3.94	-0.03	0.54	7.82	8.13	11.92	7.84	3.30	**3.70**	**0.15**	31227
-8.98	-10.07	-12.56	-3.60	-6.26	-4.09	-2.19	-5.12	**-1.69**	**-0.07**	31230
-0.84	-9.45	-5.87	9.06	11.33	16.14	17.26	22.22	**10.46**	**0.41**	40102
1.92	1.39	-1.15	3.35	-1.00	8.86	15.47	16.03	**7.04**	**0.28**	40103
-1.96	-2.26	0.50	-3.09	2.16	1.29	-3.52	-2.26	**-0.10**	**0.00**	40128
3.55	-2.30	-1.98	2.76	3.05	5.37	1.98	1.34	**1.11**	**0.04**	40129
8.54	10.95	15.25	18.57	20.87	20.87	17.96	14.89	**12.33**	**0.49**	40131
7.60	2.69	5.98	15.38	13.19	16.00	13.03	9.83	**6.38**	**0.25**	40204
-2.60	5.99	6.71	5.93	1.80	6.66	5.18	8.03	**2.26**	**0.09**	40205
10.04	6.21	8.12	7.62	8.24	14.98	7.53	9.08	**5.86**	**0.23**	40208
3.73	-0.82	5.09	11.22	12.40	18.77	7.65	3.68	**13.96**	**0.55**	40222
34.35	27.48	34.38	23.06	24.01	35.78	27.49	21.66	**12.65**	**0.50**	40224
0.70	1.95	6.28	7.56	7.09	12.40	8.78	3.21	**7.77**	**0.31**	40229
								5.13	**0.20**	
68.53	**30.52**	**93.75**	**188.92**	**212.64**	**321.59**	**242.89**	**242.59**	**154.03**		**Total (mm)**
2.70	**1.20**	**3.69**	**7.44**	**8.37**	**12.66**	**9.56**	**9.55**		**6.06**	**Total (in)**

APPENDIX 6

Multivariate Randomized Block Permutation Evaluation Output

The MRBP evaluation consisted of 3 pairs of analyses, where each pair consisted of an observed vs. control (no-seed) run analysis and a corresponding observed vs. seeded run analysis:

Set 1: All 30 SNOTEL sites (12 in target area, 18 in non-target area)
Set 2: 12 SNOTEL sites in the target area only
Set 3: 18 SNOTEL sites in the non-target area only

Set 1: Model Control for all 30 SNOTEL Sites selected from Grid 3

```
ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        1
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  1
           C(G,H) RANKS TEST EXPONENT H =    1.000000
           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      47.79195
           EXPECTED DELTA   :      63.07260
           VARIANCE OF DELTA:      9.493793
           SKEWNESS OF DELTA:    -0.6038712E-01
           AGREEMENT MEASURE:     0.2422708
           (D-E[D])/STDEV(D):     -4.959318
           P-VALUE          :     0.1061620E-05
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        2
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      38.06743
           EXPECTED DELTA   :      50.85409
           VARIANCE OF DELTA:      4.310914
           SKEWNESS OF DELTA:    -0.1323713
           AGREEMENT MEASURE:     0.2514381
           (D-E[D])/STDEV(D):     -6.158463
           P-VALUE          :     0.1911016E-07
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        3
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.5919642E-02
           EXPECTED DELTA   :     0.7264706E-02
           VARIANCE OF DELTA:     0.6431258E-07
           SKEWNESS OF DELTA:     0.4337664E-02
           AGREEMENT MEASURE:     0.1851506
           (D-E[D])/STDEV(D):     -5.303898
           P-VALUE          :     0.5668024E-07
********************************************************
```

```
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        4
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.5772113E-02
           EXPECTED DELTA   :     0.7378538E-02
           VARIANCE OF DELTA:     0.7895596E-07
           SKEWNESS OF DELTA:    -0.9659673E-01
           AGREEMENT MEASURE:     0.2177159
           (D-E[D])/STDEV(D):     -5.716998
           P-VALUE          :     0.6535702E-07
********************************************************
```

Set 1: Model Seed for all 30 SNOTEL Sites selected from Grid 3

```
ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=        1
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  1
           C(G,H) RANKS TEST EXPONENT H =    1.000000
           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      47.77647
           EXPECTED DELTA   :      63.07918
           VARIANCE OF DELTA:      9.463491
           SKEWNESS OF DELTA:    -0.6091576E-01
           AGREEMENT MEASURE:     0.2425952
           (D-E[D])/STDEV(D):     -4.974421
           P-VALUE          :     0.1000465E-05
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=        2
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      37.68800
           EXPECTED DELTA   :      50.54509
           VARIANCE OF DELTA:      4.345569
           SKEWNESS OF DELTA:    -0.1311288
           AGREEMENT MEASURE:     0.2543687
           (D-E[D])/STDEV(D):     -6.167644
           P-VALUE          :     0.1781136E-07
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=        3
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.5915833E-02
           EXPECTED DELTA   :     0.7262530E-02
           VARIANCE OF DELTA:     0.6448415E-07
           SKEWNESS OF DELTA:     0.3145884E-02
           AGREEMENT MEASURE:     0.1854308
           (D-E[D])/STDEV(D):     -5.303266
           P-VALUE          :     0.5687684E-07
********************************************************
```

```
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=         4
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  30 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.5731994E-02
           EXPECTED DELTA   :     0.7353162E-02
           VARIANCE OF DELTA:     0.8043636E-07
           SKEWNESS OF DELTA:    -0.9579678E-01
           AGREEMENT MEASURE:     0.2204723
           (D-E[D])/STDEV(D):     -5.716128
           P-VALUE          :     0.6450544E-07
********************************************************
```

Set 2: Model Control for 12 SNOTEL Sites within Target Area

```
ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=       1
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  1
           C(G,H) RANKS TEST EXPONENT H =    1.000000
           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      29.71076
           EXPECTED DELTA   :      38.62393
           VARIANCE OF DELTA:      5.722565
           SKEWNESS OF DELTA:    -0.6418420E-01
           AGREEMENT MEASURE:     0.2307681
           (D-E[D])/STDEV(D):     -3.725949
           P-VALUE          :     0.1605811E-03
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=       2
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      21.76882
           EXPECTED DELTA   :      26.40908
           VARIANCE OF DELTA:      1.440204
           SKEWNESS OF DELTA:    -0.1123770
           AGREEMENT MEASURE:     0.1757072
           (D-E[D])/STDEV(D):     -3.866614
           P-VALUE          :     0.1385117E-03
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=       3
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.3709139E-02
           EXPECTED DELTA   :     0.4403931E-02
           VARIANCE OF DELTA:     0.3317888E-07
           SKEWNESS OF DELTA:    -0.1893024E-01
           AGREEMENT MEASURE:     0.1577664
           (D-E[D])/STDEV(D):     -3.814383
           P-VALUE          :     0.8078840E-04
********************************************************
```

```
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        4
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.3643426E-02
           EXPECTED DELTA   :     0.4446900E-02
           VARIANCE OF DELTA:     0.3980798E-07
           SKEWNESS OF DELTA:    -0.1132708
           AGREEMENT MEASURE:     0.1806818
           (D-E[D])/STDEV(D):     -4.027047
           P-VALUE          :     0.8011404E-04
********************************************************
```

Set 2: Model Seed for 12 SNOTEL Sites within Target Area

```
ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=         1
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  1
           C(G,H) RANKS TEST EXPONENT H =    1.000000
           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      29.71900
           EXPECTED DELTA   :      38.63157
           VARIANCE OF DELTA:      5.723693
           SKEWNESS OF DELTA:    -0.6401185E-01
           AGREEMENT MEASURE:     0.2307067
           (D-E[D])/STDEV(D):     -3.725327
           P-VALUE          :     0.1607391E-03
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=         2
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      21.38351
           EXPECTED DELTA   :      26.04253
           VARIANCE OF DELTA:      1.458420
           SKEWNESS OF DELTA:    -0.1118805
           AGREEMENT MEASURE:     0.1789004
           (D-E[D])/STDEV(D):     -3.857921
           P-VALUE          :     0.1421757E-03
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=         3
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.3706070E-02
           EXPECTED DELTA   :     0.4405982E-02
           VARIANCE OF DELTA:     0.3348482E-07
           SKEWNESS OF DELTA:    -0.1906771E-01
           AGREEMENT MEASURE:     0.1588549
           (D-E[D])/STDEV(D):     -3.824894
           P-VALUE          :     0.7761994E-04
********************************************************
```

```
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=         4
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  12 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)        :     0.3619122E-02
           EXPECTED DELTA   :     0.4430262E-02
           VARIANCE OF DELTA:     0.4073975E-07
           SKEWNESS OF DELTA:    -0.1134710
           AGREEMENT MEASURE:     0.1830907
           (D-E[D])/STDEV(D):     -4.018709
           P-VALUE         :     0.8261498E-04
********************************************************
```

Set 3: Model Control for 18 SNOTEL Sites outside of Target Area

```
ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        1
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  1
           C(G,H) RANKS TEST EXPONENT H =    1.000000
           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)        :      36.59184
           EXPECTED DELTA  :      48.63476
           VARIANCE OF DELTA:      6.885675
           SKEWNESS OF DELTA:    -0.8807463E-01
           AGREEMENT MEASURE:     0.2476196
           (D-E[D])/STDEV(D):     -4.589429
           P-VALUE         :     0.7568070E-05
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        2
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)        :      29.35301
           EXPECTED DELTA  :      41.22324
           VARIANCE OF DELTA:      3.931875
           SKEWNESS OF DELTA:    -0.1693913
           AGREEMENT MEASURE:     0.2879500
           (D-E[D])/STDEV(D):     -5.986313
           P-VALUE         :     0.8730154E-07
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        3
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)        :     0.4367869E-02
           EXPECTED DELTA  :     0.5434131E-02
           VARIANCE OF DELTA:     0.4543774E-07
           SKEWNESS OF DELTA:    -0.3145582E-01
           AGREEMENT MEASURE:     0.1962158
           (D-E[D])/STDEV(D):     -5.002137
           P-VALUE         :     0.5254047E-06
********************************************************
```

```
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-REGULAR RUN,   EXP=        4
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.4186842E-02
           EXPECTED DELTA   :     0.5538480E-02
           VARIANCE OF DELTA:     0.5949753E-07
           SKEWNESS OF DELTA:    -0.1415608
           AGREEMENT MEASURE:     0.2440450
           (D-E[D])/STDEV(D):     -5.541292
           P-VALUE          :     0.3337998E-06
********************************************************
```

Set 3: Model Seed for 18 SNOTEL Sites outside of Target Area

```
ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=        1
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  1
           C(G,H) RANKS TEST EXPONENT H =    1.000000
           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      36.51824
           EXPECTED DELTA   :      48.64707
           VARIANCE OF DELTA:      6.891588
           SKEWNESS OF DELTA:    -0.8717303E-01
           AGREEMENT MEASURE:     0.2493229
           (D-E[D])/STDEV(D):     -4.620183
           P-VALUE          :     0.6612415E-05
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=        2
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  0
           DELTA(D)         :      29.22745
           EXPECTED DELTA   :      41.19064
           VARIANCE OF DELTA:      3.978976
           SKEWNESS OF DELTA:    -0.1650927
           AGREEMENT MEASURE:     0.2904346
           (D-E[D])/STDEV(D):     -5.997375
           P-VALUE          :     0.7678781E-07
********************************************************
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=        3
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  0
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.4367314E-02
           EXPECTED DELTA   :     0.5436646E-02
           VARIANCE OF DELTA:     0.4552693E-07
           SKEWNESS OF DELTA:    -0.3393653E-01
           AGREEMENT MEASURE:     0.1966897
           (D-E[D])/STDEV(D):     -5.011623
           P-VALUE          :     0.5255164E-06
********************************************************
```

```
 ANALYSIS OF RANDOMIZED BLOCK EXPERIMENT (MRBP):
    COMPARISON OBS-SEEDED RUN,   EXP=         4
    DISTANCE FUNCTION EXPONENT:  1.00
    WITH  18 RESPONSES,   2 BLOCKS,  30 GROUPS.

   RESULTS OF MRBP ANALYSIS:
           1 (0) INDICATES (NO) C(G,H) RANKS TEST:  0

           1 (0) INDICATES (NO) MEDIAN ALIGNMENT:  1
           1 (0) INDICATES (NO) AVE. DIST. COMMENSURATION:  1
           DELTA(D)         :     0.4161504E-02
           EXPECTED DELTA   :     0.5527443E-02
           VARIANCE OF DELTA:     0.6071251E-07
           SKEWNESS OF DELTA:    -0.1390008
           AGREEMENT MEASURE:     0.2471194
           (D-E[D])/STDEV(D):     -5.543603
           P-VALUE          :     0.3164337E-06
********************************************************
```